January 2005

Performance Analysis of Composite Repair of Sandstone

Scott M. Pons
University of Pennsylvania

Presented to the Faculties of the University of Pennsylvania in Partial Fulfillment of the Requirements for the Degree of Master of Science in Historic Preservation 2005.
Advisor: Frank G. Matero

Performance Analysis of Composite Repair of Sandstone

Comments
Presented to the Faculties of the University of Pennsylvania in Partial Fulfillment of the Requirements for the Degree of Master of Science in Historic Preservation 2005.
Advisor: Frank G. Matero

PERFORMANCE ANALYSIS OF COMPOSITE REPAIR OF SANDSTONE

Scott Michael Pons

A THESIS

in

Historic Preservation

Presented to the Faculties of the University of Pennsylvania in
Partial Fulfillment of the Requirements for the Degree of

MASTER OF SCIENCE

2005

Advisor	Reader
Frank G. Matero	John Hinchman
Professor of Architecture	Lecturer in Historic Preservation

Program Chair
Frank G. Matero
Professor of Architecture

ACKNOWLEDGEMENTS

Many people contributed significantly to the preparation of this thesis. Foremost, I would like to thank my advisor, Frank Matero. His insight, expertise and critical perspective helped to shape my work. I am also very grateful for the assistance and advice of my reader, John Hinchman. I owe special thanks to Dr. Alex Radin of the Laboratory for Research on the Structure of Matter and Dennis Pierattini of the School of Design Fabrication Lab.

Lastly, I want to thank my family, friends and classmates for their encouragement and support.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF GRAPHS

List of Tables

CHAPTER 1 – INTRODUCTION

1.1 USE OF SANDSTONE AS A BUILDING MATERIAL

Sandstone has been one of the major commercial building stones in North America since at least the middle part of the nineteenth century. In the Northeast, especially in cities such as New York, Boston, and Philadelphia, brown sandstone, or brownstone, was preferred for its range of colors, tan to dark brown and red, first in ecclesiastical buildings and later in residential row houses.[1]

By the late nineteenth century, however, the brown sandstone had earned a reputation as an unsuitable material in the Northeast. Buildings less than five years old began to exhibit excessive decay.[2]

1.2 SANDSTONE DECAY

There are three primary factors related to the decay of sandstone: mineralogical composition and the physical make-up of the stone fabric; environment, or exposure to damaging agents such as water, salt and corrosive chemicals; and use, how the stone is quarried, shaped, and installed in a structure.[3]

---

[1] Frank G. Matero and Jeanne Marie Teutonico, "The Use of Architectural Sandstone in New York City in the 19th Century," *APT Bulletin* 14 (no. 2, 1982): 11.
[2] Alexis A. Julien, "The Decay of the Building Stones of New York City," *Transactions of the New York Academy of Sciences* 2 (no.4, 29 January 1883): 73-74.
[3] James W. Dossett, "Composite Repair of Sandstone" (Master's Thesis, University of Pennsylvania, 1998), 1.

1.2.1 Composition

Sandstone is a clastic sedimentary rock. Also known as layered rocks, sedimentary rocks are formed by one of two processes. Clastic sedimentary rocks form through the accumulation of rock particles by water or wind action. Organic/chemical sedimentary rocks form by accumulation of organic material or by chemical precipitates from ocean water.[4] In most clastic sedimentary rocks, including sandstone, the grains are quartz. Quartz is a hard, chemical-resistance silicate mineral not directly attacked by most weathering agents; however, the size and shape of the grains are responsible for the pore size and texture of the rock. Pore space is a major factor in the durability of the stone. This is discussed in greater detail in section 1.2.2.

The grains of the sandstone are held together by one of four types of cementing matrix: 1) siliceous, in which silica or silicon dioxide is the binder; 2) calcareous, in which calcite is the binder; 3) ferruginous, in which iron oxides, usually limonite, are the binder; and 4) argillaceous, in which clays are the binder. Some sandstones have more than one type of binder.[5] The importance of the matrix in determining the durability of the stone was recognized as early as the 1880's.[6] The matrix can be attacked by water or by water- or air-borne corrosive agents. The relationship of the cementing matrix to decay is discussed in greater detail in section 1.2.2.

---

[4] Erhard M. Winkler, *Stone in Architecture: Properties, Durability,* 3d ed. (Berlin, Heidelburg, New York: Springer-Verlag, 1994), 19.
[5] Eugene C. Robertson, "Physical Properties of Building Stone," in *Conservation of Historic Stone Buildings* (Washington: Committee on Conservation of Historic Stone Buildings and Monuments, National Materials Advisory Board, Commission on Engineering and Technical Systems, National Research Council, 1982), 82.
[6] Julien, 74.

The structure of sandstone is the final aspect of composition related to decay. Sandstone is a sedimentary rock formed in layers as the grains are deposited. Structure is the type and thickness of the layers or beds.[7] The thickness of the beds can range from less than one inch to many feet. The seams between the beds are a natural line of weakness in the stone (discussed in section 1.2.3).

Sandstone's aggregate, matrix, and structure, along with its geographical source and color, combine to classify the sandstone. For example, the stone used in this research is from the Connecticut River Valley. It is a red/brown ferruginous sandstone with primarily quartz aggregate. It has medium-sized grains and beds of 2 to 18 feet thick, although tremendous variations in fabric exist.[8]

1.2.2 Environment

The second major influence on the decay of sandstone is the environment. The stone is exposed to damaging agents like water, salt, wind, atmospheric pollution, and microorganisms. Human contact can damage a building through misuse, or acts of vandalism. The environment of any structure is a complicated system, and it is rare that any single decay mechanism occurs alone. Water is the most crucial factor in sandstone decay because it is itself damaging, and it is the delivery agent for many other decay mechanisms.

---

[7] Winkler, 15.
[8] Dossett, 3.

The arrangement of the grains in the stone results in open spaces or pores. These pores allow liquid water and water vapor to travel through the stone. Water can come from the atmosphere in the form of rain or vapor or it can come from the ground. Water alone can damage sandstone through the processes of hydric dilatation, the volumetric expansion of a material in the presence of liquid water, and hygric dilatation, expansion in a humid environment.[9] Argillacious or clay-bound sandstones are particularly vulnerable because clays swell a great deal.[10] Hydric and hygric dilatation can damage the stone by breaking the bonds between grains and thereby dislodging the grains. Although the stone will contract to its original dimension when it dries, wet/dry cycling and its resultant expansion and contraction can cause material fatigue and more serious damage.[11] The combination of water and freezing temperature results in a similar decay mechanism. Water expands when it freezes displacing grains and eventually dislodging them. The joints between the beds are a natural weak point in the stone and are particularly vulnerable to these types of decay.

Water also carries dissolved salts into the stone. Some soluble salts are present in the stone when it is quarried. Other sources of salts include groundwater, sea spray, deicing salts, and cements used in mortars.[12] It has been demonstrated that damage to sandstone from salt occurs when dissolved

[9] R. Snethlage and E. Wendler, "Moisture Cycles and Sandstone Degradation," in *Report of the Dahlem Workshop on Saving Our Architectural Heritage: The Conservation of Historic Stone Structures Held in Berlin 3-8 March 1996*, eds. N.S. Baer and R. Snethlage (Chichester, New York, Weinheim, Brisbane, Singapore, and Toronto: John Wiley & Sons, 1997), 9.
[10] Robertson, 82.
[11] Snethlage and Wendler, 9.
[12] Winkler, 157-59.

salts are deposited in the pores near the surface of the stone.[13] The salts expand when they crystallize and cause a thin layer of the stone to blister or turn to powder. Decay will continue under this initial layer. One published study explains how this type of decay, ranging from dislodging of individual grains to scaling up to 2 cm thick, can occur.[14] Salt concentrates and crystallizes in the part of the stone where water is retained in the pores the longest, not necessarily near the surface. The depth of the zone of maximum water content varies according to the pore size and distribution of the particular stone, as well as conditions on the building. Surfaces exposed to sun and wind will dry quickly, meaning the area that remains wet and attracts salts lies beneath the surface. Damage to the stone will be manifested by the formation of scales. Surfaces that are sheltered and retain moisture will exhibit granular detachment, or “sanding off”.[15]

Some salts will hydrate, absorbing water into the crystal lattice of the salt. Hydration and dehydration depend on temperature and relative humidity. Hydration increases the volume of the salt, putting pressure on the pore walls. The amount of expansion and the rate depend on conditions and the type of salt.[16]

Plants and animals ranging from the smallest (bacteria, algae, fungi, and lichens) to the largest (trees, birds, and humans) will attack stone chemically and mechanically. Biodeterioration of stone is a complex and not fully understood

---

[13] S.Z. Lewin, “The Mechanism of Masonry Decay Through Crystallization,” in *Conservation of Historic Stone Buildings* (Washington: Committee on Conservation of Historic Stone Buildings and Monuments, National Materials Advisory Board, Commission on Engineering and Technical Systems, National Research Council, 1982), 120.
[14] Snethlage and Wendler, 17-18.
[15] Ibid., 18.
[16] Winkler, 169.

process involving three stages of development: 1) the stone is colonized by air- and water-borne organisms; 2) decay is initiated; and 3) the damaged stone flakes or disintegrates and the process begins again on the new surface.[17] Certain bacteria attack minerals directly by producing corrosive chemicals. Algae, fungi, and mosses as well as higher plants can mechanically attack stone by expanding within the pores or by producing organic acids that damage constituent minerals. They can also trap moisture within the stone. Scaling of sandstone similar to salt decay is possible through the action of algae that can penetrate deeply into the stone.[18]

1.2.3 Use

The final major influence on the durability of sandstone is how the stone is tooled and set in place. Sandstone is a sedimentary rock, and bedding seams are a natural line of weakness. Quarrymen exploit these seams when cutting sandstone.[19] The stone is best set with the bedding planes parallel to the ground. If set on edge, water is more likely to get into the seams and split the stone. Each bed also has slightly different composition and different mechanical properties. If set on edge, differential stresses between the beds are created as the weight of the masonry above puts load on the stone. This creates shear stress along the

---

[17] R.J. Koestler, T. Warscheid, and F. Neito, "Bioterioration: Risk Factors and Their Management," in *Report of the Dahlem Workshop on Saving Our Architectural Heritage: The Conservation of Historic Stone Structures Held in Berlin 3-8 March 1996*, eds. N.S. Baer and R. Snethlage (Chichester, New York, Weinheim, Brisbane, Singapore, and Toronto: John Wiley & Sons, 1997), 27.
[18] Winkler, 224.
[19] Oliver Bowles, *The Stone Industries* (New York and London: McGraw Hill, 1934), 80.

bedding planes and can cause the stone to split.[20] The problem is worse if the stone is set with the bedding planes perpendicular to the ground and parallel to the face of the wall. This is known as face-bedding. The outermost bed is unsupported on one side and prone to delaminate from the wall.

There is no agreement on what agent is most responsible for the decay of sandstone. It has been claimed that the stone is inferior and not suitable for the Northeast climate.[21] On the other hand, it has been stated that there is nothing wrong with the stone as long as it is quarried, cut, and set correctly.[22] In any event, there are many buildings in need of treatment due to poor stone selection and use.

1.3 Sandstone Treatments

Composite repair is a method of replacing lost or damaged areas of stone by filling the area of loss with a material that hardens in place and bonds to the substrate. Composite repair of sandstone is not typically an isolated treatment. In most cases, it is just one element of a larger conservation program that may include many different treatments such as cleaning, removal of soluble salts, consolidation, and other types of repair including mechanical pinning, adhesive repair, replacement in kind, and replacement with artificial products such as cast stone.

[20] Dossett, 7.
[21] Julien, 75.
[22] Bowles, 70.

1.3.1. Cleaning

If a treatment plan includes cleaning, it is best to clean the stone before beginning composite repair.[23] The composite repair material, once cured, must have a color similar to that of the cleaned stone. If the repair is color matched to the soiled stone, the repair will stand out in contrast to the surrounding surface after the building is cleaned. When it is not possible to clean the building before installing composite repairs, a test area can be cleaned for determining the color of the repair material, and the repair can be temporarily colored to blend with the surrounding soiled stone until the building is cleaned in the future. Three general methods of stone cleaning are commonly used: 1) water washing; 2) abrasive cleaning; and 3) chemical cleaning.[24] The method of cleaning must be appropriate for the repair material as well as the stone. For example, an abrasive cleaning method that is suitable for the stone but too aggressive for a softer repair will erode the repair and create a relief between the stone and the repair. The relief can trap water and soiling leading to more rapid deterioration.

Due to the damage caused by salts, their removal from the stone is often included in treatments plans. There are three general methods used for salt removal: 1) rinsing the surface with water to dissolve salts and carry them away from the building; 2) poulticing which involves packing an absorbent material onto the surface of the stone to remove dissolved salts; and 3) rinsing the surface

---

[23] John Ashurst and Francis G. Dimes, eds., *Conservation of Building & Decorative Stone,* vol. 2(Oxford: Butterworth Heinemann, 1998), 24.
[24] Winkler, 276-80. David W. Boyer, "Masonry cleaning – The State of the Art," in *Cleaning Stone and Masonry: A Symposium Sponsored by ASTM Committee E-6 on Performance of Building Constructions Held in Louisville, KY 18 April 1983,* ASTM STP 935, ed. James R. Clifton (Philadelphia: American Society for Testing and Materials, 1986), 31.

combined with a suction device to extract the water and dissolved salts. If a treatment plan includes salt removal, it should be done before composite repair to minimize the risk of crystallization at the interface between the stone and the repair.

1.3.2 Consolidation

Weathering of sandstone causes loss of grain to grain cohesion either at the surface or below the surface. If the loss of cohesion occurs at the surface the resulting damage is disaggregation, dislodging of individual grains from the stone, while loss of cohesion beneath the surface results in flaking or scaling.[25] Consolidation attempts to replace lost cementing material, increase grain to grain cohesion, adhere the decayed area to sound stone, and render the stone more resistant to future decay.[26]

The basic principle of stone consolidation is to introduce a compound that will penetrate into the stone and reestablish grain to grain cohesion either by forming a bridge between grains or by forming a continuous film.[27] However, the consolidated stone must not be made stronger than the unconsolidated stone or

---

[25] H.R. Sasse and R. Snethlage, "Methods for the Evaluation of Stone Conservation Treatments," in *Report of the Dahlem Workshop on Saving Our Architectural Heritage: The Conservation of Historic Stone Structures Held in Berlin 3-8 March 1996*, eds. N.S. Baer and R. Snethlage (Chichester, New York, Weinheim, Brisbane, Singapore, and Toronto: John Wiley & Sons, 1997), 235.
[26] M. Laurenzi Tobasso, "Conservation Treatments of Stone," in *Conservation of Historic Stone Buildings* (Washington: Committee on Conservation of Historic Stone Buildings and Monuments, National Materials Advisory Board, Commission on Engineering and Technical Systems, National Research Council, 1982), 280.
[27] Sasse and Snethlage, 235-36.

the strengthened zone at the surface can scale off.[28] The consolidated stone must also be compatible with the unconsolidated stone in terms of color, water absorption, water vapor transmission, and thermal expansion. If a treatment plan includes both consolidation and composite repair, which inevitably alters the properties of the stone, consolidation usually takes place before composite repair.[29] Consolidating first helps to ensure that composite repairs are applied to sound stone and may eliminate the need to chisel the area to be repaired.

1.3.3 Repair

There are many methods of treatment for replacing lost stone, and they fall into two general categories: replacement and composite repair.[30] Replacement involves filling the area of loss by attaching a piece of stone or cast material, or replacing the entire damaged masonry unit with stone or cast material. Composite repair is a method of replacing lost or damaged areas of stone by filling the area of loss with a material that hardens in place and bonds to the substrate. Carving new stone is costly and time-consuming, and it requires skill that may not be available.[31] It can also be difficult to find matching stone.[32] Casting a replicate stone can be a cost effective alternative, but it requires an undamaged element to make a mold if the lost element is carved, and some

[28] Ibid., 235.
[29] Helmut Weber and Klaus Zinsmeister, *Conservation of Natural Stone: Guidelines to Consolidation, Restoration and Preservation* (Ehninger: expert-Verlag, 1991), 101.
[30] John Griswold and Sari Uricheck, "Loss Compensation Methods for Stone," *Journal of the American Institute for Conservation* 37 (1998): 91.
[31] Ibid.
[32] Norman R. Weiss et al., *Sandstone Restoration Study* (New York: New York Landmarks Conservancy, 1982).

stones are difficult to match. The most critical aspect of stone replacement is the joint between the new work and the old.[33] The joint must be strong enough to bear the weight of the new work but not so strong as to damage the surrounding stone.

1.4 Composite Repair

Composite repair is generally reserved for shallow or isolated stone losses, less than two inches in depth, on flat wall areas, and for rebuilding corners, carvings, or relief areas.[34] The former condition is most common where the stone has been face-bedded, and the later is found on cornices, lintels, sills, and portals.

Proper application is required for a successful composite repair. It is recommended to chisel out all deteriorated substrate, and/or consolidate the area to be repaired. The area should to square cut without feathered edges. All debris must be removed, and the surface cleaned. Mechanical keying for the composite repair material can be created by drilling or chiseling the surrounding surfaces, or inserting non-corroding anchors or pins. Depending on the type of composite repair material, the stone surface may need pre-wetting.

1.4.1 Critical Properties

Composite repair materials consist essentially of a mixture of binders and aggregates, with pigments or other additives to give the material the necessary

[33] Griswold and Uricheck, 92
[34] Ashurst and Dimes, 24.

properties. Several sources culled from the literature, which are by no means exhaustive, discuss the properties of composite repair materials for stone.[35] The following sections provide a summary of the performance properties that these sources indicate are critical for any composite repair. The specific tests identified were chosen for ease of performance, low cost and reproducibility of implementation, availability of materials and equipment, and capability of being conducted within the time constraints.

1.4.1.1 CONSISTENCY

Consistency is related to the stiffness of fresh mortar. This is an important factor in composite repair because the mortar must be plastic enough to be pushed into the area being filled, yet stiff enough to stay where it is applied long enough to set. According to the European Standard EN 1015-3: 1995 E *Determination of Consistence of Fresh Mortar (by Flow Table)*, consistency is defined as:

> a measure of the fluidity and/or wetness of the fresh mortar and gives a measure of the deformability of the fresh mortar when subjected to a certain type of stress. The consistence however is

[35] John Ashurst and Nicola Ashurst, "Mortars, Plasters and Renders," in *Practical Building Conservation,* vol. 3 (Hants, England: Gower Technical Press, 1988); Michael P. Edison, "Custom Latex-Modified Cement Repair Mortars for Masonry," *Concrete Repair Bulletin* (July-August 1991): 7-9,22; A.S. Iveson, *Masonry Conservation and Restoration* (London: Attic Books, 1987); P.R Hill and J.C.E. David, *Practical Stone Masonry* (London: Donhead, 1995); Dean Korpan, "Composite Stone Repairs at Drayton Hall," *APT Bulletin* 14 (no. 3, 1982); Michael F. Lynch and William J. Higgins, *The Maintenance and Repair of Architectural Sandstone* (New York: New York Landmarks Conservancy, 1982); S Peroni et al., "Lime-Based Mortars for the Repair of Ancient Masonry and Possible Substitutes," in *Mortars, Cements and Grouts Used in the Conservation of Historic Buildings: Symposium Held in Rome 3-6 November 1981* (Rome: ICCROM, 1982); C. Selwitz, *Research in Conservation: 7, Epoxy Resins in Stone Conservation* (Marina Del Rey: Getty Conservation Institute, 1992); Giorgio Torraca, *Porous Building Materials: Materials Science for Architectural Conservation,* 3d ed. (Rome: ICCROM, 1988); Weiss et al.

> not directly associated with the manner in which the fresh mortar handles when used by a craftsman.[36]

EN 1015-3: 1995 E was used for reference only, and the consistency of the mortars was measured according to ASTM C1437-99 *Standard Test Method for Flow of Hydraulic Cement Mortar*.

1.4.1.2 *Setting Time*

Setting time measures the rate at which mortars harden under specific laboratory conditions. Setting time measurement is important when evaluating the applicability of mortar formulations used for composite repair. For example, fast drying mortar may be needed for use in moist climates with a risk of frost. Similarly, slow drying mortar may be necessary in arid climates where mortar could dry and shrink too rapidly. Setting time is affected by the temperature and amount of water used for mixing, the length of mixing time, and the temperature and humidity of the air in which the mortar is stored. Setting time of the mortars is determined according to ASTM C191-99 *Standard Test Method for Time of Setting of Hydraulic Cement by Vicat Needle*.

1.4.1.3 *Dimensional Stability*

Dimensional stability refers to how much mortar shrinks as it cures, and to how much a mortar expands and contracts in reaction to changes in temperature and moisture content. A composite repair mortar should have minimal shrinkage

---

[36] EN 1015-3: 1995 E, “Methods of Test for Mortar for Masonry – Part 3: Determination of Consistency of Fresh Mortar (by Flow Table),” (Brussels: European Committee for Standardization, 1995), 4.

as it cures to prevent cracking. If the repair shrinks too much it will crack, pull away from the stone, or even worse damage the stone. In any case, the entry of water will accelerate the decay of the repair and the stone. Once cured, the repair should have expansion and contraction properties similar to that of the surrounding stone, so that the repair moves with the stone and not against it. If the repair expands more than the stone, the stone may be damaged; and if the repair expands less, cracking of the repair may occur or the bond between repair and stone may be weakened prematurely. Drying shrinkage of the mortars is measured according to ASTM C1148-92a *Standard Test Method for Measuring the Drying Shrinkage of Masonry Mortar*.

Measurement of the coefficient of thermal expansion of the mortars and the Connecticut brownstone is conducted according to ASTM 531-00 *Standard Test Method for Linear Shrinkage and Coefficient of Thermal Expansion of Chemical-Resistant Mortars, Grouts, Monolithic Surfacings, and Polymer Concretes*. Hydric expansion, the increase in length due to the absorption of water, of the mortars and the stone is determined according to RILEM II.7 – *Linear Strain Due to Water Absorption*. No known testing standard exists to measure hygric expansion, the increase in length in a humid environment.

1.4.1.4 *Water Vapor Transmission*

Water vapor transmission is the ability for water vapor to pass through a material. The test for water vapor transmission aids in determining the permeability of the material. Permeability in this case is the movement of water vapor through the pores, voids, and cracks in the composite repair mortar. The inevitable presence of water vapor in a masonry system requires a mortar which can allow for its movement through the system. It is important for the composite used to transmit water vapor at a rate equal to or preferably greater than the surrounding stone. Otherwise, water vapor is concentrated in the stone where it is likely to condense within the pores of the stone, accelerating decay, or it is trapped at the interface between the repair and the stone, weakening the bond. Water vapor transmission for the mortars and the stone is determined according to ASTM E96-00 *Standard Test for Water Vapor Transmission of Materials*.

1.4.1.5 *Water Absorption*

Water absorption is the ability of a material to absorb liquid water. The capacity with which a mortar can absorb water addresses similar desirable qualities sought to be quantified by the water vapor transmission test. If water moves through the stone and is impeded at the interface with the composite repair due to an incompatible imbibition capacity relative to the stone, the water can accelerate decay at the composite/stone interface. This water saturation causes a weakness at the bond surface and encourages the deposition of soluble salts. It is therefore important to investigate the mortar's ability to absorb water and to compare it to that of the stone. More importantly, this test makes it possible to calculate apparent porosity which can suggest several behavior characteristics of the mortar itself and in relation to the stone. The water absorption test is conducted, with mortar and stone samples, in accordance with NORMAL 7/81: *Water Absorption by Total Immersion – Imbibition Capacity*.

1.4.1.6 *STRENGTH*

There are many ways to describe the strength of a material. For composite repair, the three most critical aspects of strength are flexural strength, elasticity, and bond strength. Composite repairs are not structural and therefore not required to bear the weight of the surrounding masonry. The stress endured by a composite repair is induced by differential movement of the repair and the stone through thermal expansion and swelling from water absorption. Flexural strength is a measure the mortar’s resistance to cracking under bending stress. Elasticity describes the stiffness of the mortar, or how well it withstands bending. The composite repair material should have a high resistance to cracking and be flexible enough to absorb stress caused by movement. The microcracking resulting from a failure to withstand bending stress encourages large crack propagation and introduces voids for moisture and salts to accumulate and accelerate decay. Similarly, the strength of an appropriate composite repair mortar is relative to the surrounding stone. If the mortar withstands more bending load than the stone, failure may occur in the stone rather than the mortar. Flexural strength and elasticity of the repair mortars and the stone are tested independently according to ASTM 531-00 *Standard Test Method for Linear Shrinkage and Coefficient of Thermal Expansion of Chemical-Resistant Mortars,* *Grouts, Monolithic Surfacings, and Polymer Concretes*. Bond strength is discussed in greater detail in section 1.4.1.8.

1.4.1.7 *DURABILITY*

Broadly defined, the durability of a composite repair is a measure of how well the repair withstands the corrosive or abrasive effects of the environment. However, a composite repair should not be durable at the expense of the stone. There are numerous ways to test durability, but this research will only investigate salt crystallization resistance and frost resistance.

Salt is an aggressive deteriorating substance that moves with moisture through the pores of a masonry system. The investigation of the porosity of a composite repair mortar in conjunction with the mortar's resistance to salt will suggest some behavior patterns of the mortar and its durability in a masonry system. It is necessary to have a mortar that resists the attack of salt but in a manner that is more beneficial to the surrounding stone. If a mortar withstands the threat of salt so successfully as to severely damage the stone, that resistance behavior is undesirable. If a mortar does not withstand the salt attack well, but does allow for the movement of salt in solution to the exterior, the salt will effloresce at the surface which is preferable to its accumulation within the masonry system. The mortars' resistance to salt attack is measured in accordance with RILEM V.1b – *Crystallization Test by Total Immersion (for Treated Stone)* because there is no known salt resistance test specifically for mortars.

Frost resistance is a measure of a mortar's ability to withstand decay due to cycles of freezing and thawing. Frost resistance is an important aspect of this research because sandstone has been used extensively throughout the Northeast. A composite repair mortar should be reasonably resistance to freeze/thaw cycling so as not to require frequent retreatment. Resistance of the mortars to freeze/thaw cycling is determined according to RILEM V.3 – *Frost Resistance*.

1.4.1.8 *Bond Strength*

A composite repair should have sufficient bonding capability to adhere to the surrounding stone. However, the bond must not be so strong that the stone is damaged if the repair fails or must be removed. While important, bond strength is not tested in this research due to the unavailability of a sufficient number of stone samples. It is assumed, based on previous research, that all of the mortar formulations tested would provide acceptable bond strength. ASTM D905 *Standard Test Method for Strength Properties of Adhesive Bonds in Shear by Compression Loading*, which is intended primarily as an evaluation of adhesives for wood, was modified for implementation in previous research.

1.4.1.9 *Color and Texture*

It is given that a composite repair should resemble the stone itself. The degree to which a repair must duplicate the appearance of the stone depends on its location. For example, a repair at ground level is subject to closer scrutiny than one on an upper level. Current conservation practice suggests that composite repair should closely match the color and texture of the stone but still be discernible from the stone. The color of a composite repair is influenced by the aggregate, the binder(s), and the use of pigments. An appropriate texture is achieved by using aggregate that resembles the stone and by tooling the repair once it has set. While acknowledging their importance, this research does not address color or texture matching of the repair mortars to the stone. The mortars tested in this research use an aggregate that provides acceptable texture match with the assumption that they could be further pigmented to match the stone's color.

1.5 Composition

The properties discussed in section 1.4.1 are controlled by manipulating the constituent parts of the composite repair mortar – aggregates, binders, and additives. Each part of the composite repair material plays a significant role in determining the properties of the material.

1.5.1 Aggregates

Aggregates greatly influence the properties of a composite repair mortar. Aggregates act as a bulking medium and impart benefits to control shrinkage of the mortar and provide strength. As with natural sandstone, the size and shape of the aggregates and their particle size distribution affect the pore size and distribution of the cured repair, and thereby its water absorption and water vapor transmission. In addition, aggregates are primarily responsible for the color and texture of the repair mortar and must be carefully matched to the surrounding stone. For sandstone repair, the aggregate is either silica sand or crushed stone. ASTM C144 *Standard Specification for Aggregate for Masonry Mortar* stipulates the grain size distribution of aggregates for use in masonry mortar.

1.5.2 Binders

Binders, as their name suggests, hold together all the other components of a repair mortar. They also bond the repair mortar to the surrounding stone. The binder can aid or inhibit several properties of a mortar such as plasticity and workability of the fresh mortar and porosity and strength of the cured mortar. Thus, the binder significantly affects the overall performance of the mortar.

Traditional water activated binders can be classified into two broad categories: inorganic and organic.[37] Inorganic binders include lime and hydraulic lime, natural and artificial hydraulic cements, and gypsum. Organic binders primarily include epoxies resins, polyester resins, and acrylic emulsion admixtures. Gypsum and organic binders are not commonly used for composite repair of sandstone, while lime, hydrated hydraulic lime, and Portland cement are widely cited as binders for composite repair mortars.

[37] Dossett, 17.

1.5.2.1 *Lime Putty and Hydrated Lime*

Both lime putty and hydrated lime begin as limestone, which is composed primarily of calcium carbonate ($CaCO_3$) and contains varying proportions of magnesium carbonate ($MgCO_3$) with minor amounts of other minerals. The rock is calcined at temperatures near 10000°C (18000°F), which drives off chemically combined carbon dioxide. Calcined limestone, which consists of oxides of calcium (CaO) and magnesium (MgO), is called quicklime. It is characterized by fast reaction with water, during which it releases significant amounts of heat. It is this material which traditionally required extended "slaking" in water before it could be used in masonry work.

Hydrated lime is produced by combining the dry, pebbly quicklime with a carefully controlled amount of water converting the oxides to hydroxides – $Ca(OH)_2/Mg(OH)_2$. All of the water is chemically combined with the quicklime, so the product remains a "dry", free-flowing powder. If more water is added, the result is lime putty. Lime putty was the traditional pre-industrial era material used, because excess water was needed to assure complete hydration when using relatively inefficient manual slaking methods. The only difference between hydrated lime and lime putty is the amount of water that has been added to them.

Both lime putty and hydrated lime contain variable amounts of calcium hydroxide and magnesium hydroxide, based on the composition of the limestone used to make them. Dolomitic limestone, with a magnesium content of 35% to 46%, is favored for use in producing lime for masonry applications due to superior water retention. Lime based on high calcium limestone, less than 5%

magnesium carbonate, is generally considered less reliable than dolomitic lime.[38] Lime cures by absorbing carbon dioxide from the air to form calcium carbonate/magnesium carbonate. The mineralogical composition of the lime putty and hydraulic limes used in this research are discussed in section 2.2.1.1. Lime putty and hydrated lime are commercially available in the United States.

Lime putty has good plasticity and a long set time, making application easier. Cured lime putty is less strong and more porous than Portland cement, but this can be an advantage if the surrounding stone is deteriorated. In this case, a stronger, denser repair material may result in failure of the stone rather than the repair. Long set time is also a significant drawback to lime putty because it inhibits the repair mortar from reaching the necessary strength. Lime putty, also know as non-hydraulic lime, does not set in the presence of water which is undesirable in moist climates.

Hydrated limes, also known as hydraulic limes because they set in the presence of water, are classified into three types: feebly hydraulic, moderately hydraulic, and eminently hydraulic. Feebly hydraulic limes have a clay content up to 10%, moderately hydraulic limes contain up to 20% clay, and eminently hydraulic limes contain greater than 20%.[39]

Flexural strength and modulus of elasticity generally increases from feebly to moderately to eminently hydraulic lime. Setting time, drying shrinkage, permeability, and water absorption generally decreases from feebly to

---

[38] The National Lime Association, online, internet 15 July 2005, available: http://www.lime.org.
[39] P.R. Hill and J.C.E. David, *Practical Stone Masonry* (London: Donhead, 1995), 176.

moderately to eminently hydraulic lime. Hydraulic limes can best be described as combining certain properties of Portland cement and lime putty. Their setting time, drying shrinkage, permeability, water absorption, and strength are typically higher than those of lime putty but lower than cement.

1.5.2.2 *Portland Cement*

Portland cement has become the standard binder for masonry mortar. In the United States it is widely used in combination with lime putty as binder for composite repair mortars. Portland cement has a fast set time and high strength. It has low water vapor transmission and water absorption that can limit its application to porous stone. Its high strength can also damage the surrounding stone. Portland cement is commercially available as a fine white or gray powder. White Portland cement was chosen over the ordinary gray Portland cement for use in this research because it is easier to color with pigments and more appropriate for a custom mortar that may require tinting.[40]

1.5.3 Additives

Many different materials can be added to cement and lime to alter the properties of the composite repair material. The most common additives are acrylic emulsions that increase bond strength and reduce water permeability, air-entraining agents that decrease density and increase porosity which helps to

[40] Weiss et al., *Sandstone Restoration Study*.

prevent damage from freeze/thaw cycling, and coloring agents such as pigments and stone dust.

Chapter 2 – Methodology

2.1 Past Research

Past research on composite repair mortars for sandstone was conducted at the University of Pennsylvania in 1998.[41] A summary of the constituent materials and mortar formulations implemented is presented below. The results of the past research will be discussed in Chapter 5. This research provided the basis for designing the current testing methodology.

2.1.1 Materials

The selection of composite repair mortars in the past research was based upon three main criteria: 1) the ingredient materials must be representative of materials recommended or used in other case studies and published sources; 2) the mixes must have enough similarities to each other to make comparison possible; and 3) the material components must be commercially available.

2.1.1.1 *Binders*

Three different binders were included in the past research: 1) Niagara Mature Lime Putty, which is a dolomitic lime putty manufactured by GenLime Group, L.P., Genoa, Ohio; 2) a moderately hydraulic hydrated lime manufactured by Riverton Corporation, Front Royal, Virginia; and 3) white Portland cement (Type I) manufactured by Riverton Corporation.

---

[41] Dossett, "Composite Repair of Sandstone."

2.1.1.2 *Sand Aggregate*

A commercially available sand aggregate, Schofield #236, was chosen for all the mortar mixes tested. This sand was chosen primarily because it displayed an acceptable color and texture match to the sandstone used in the research. The sand was also one of the sands (then known as Schofield #147) used in the Sandstone Restoration Study by the New York Landmarks Conservancy.[42]

2.1.1.3 *Acrylic Admixture*

The admixture included in the testing was Acryl® 60, an acrylic polymer emulsion manufactured by Harris Specialty Chemical for use as an internal admixture for Portland cement mortars, plaster, stuccos, and concrete mixes for improved adhesion, cohesion, and compressive and flexural strength according to the manufacturer.

2.1.1.4 *Commercial Composite Repair Material*

One commercial composite repair material, Jahn M 70 #2®, was chosen for comparison with the custom mortar formulations tested. Though there are several commercial products on the market, none were included in the current research because ample data is available from their manufacturers.

---

[42] Weiss et al., *Sandstone Restoration Study*.

2.1.1.5 *Stone*

Compatibility testing was conducted using the brown sandstone from the Portland Brownstone Quarries in Portland, Connecticut. This stone was chosen because it was used widely as a building stone in the United States in the 18th, 19th, and early 20th centuries.[43] The past research also indicated that the Portland, Connecticut quarry had recently been reopened.

2.1.2 Composite Repair Formulae

All mortar samples were formulated with a 1:3 binder to sand ratio by volume. This is a common proportion for masonry mortar, and it has been recommended for composite repair in numerous sources.[44] A description of the mortar formulations and the stone used in the past research is presented in Table 2.1.

Table 2.1: Repair Mortars and Stone Tested in Past Research (Dossett)

Sample Designation	Proportions (by volume)				
	White Portland Cement	Hydrated Hydraulic Lime	Lime Putty	Sand (Schofield #236)	Acryl 60
A	---	---	1	3	---
B	---	---	1	3	~1:5
C	---	1	---	3	---
D	---	1	---	3	~1:5
E	1	---	1	6	---
F	1	---	1	6	~1:5
G	1	---	2	9	---
H	1	---	2	9	~1:5
I	Jahn M70 #2 mixed according to manufacturer's specifications				
S	Sandstone from the Portland Brownstone Quarries, Connecticut				

[43] Dossett, 31.
[44] Ibid., 32.

2.2 Current Research

The current research seeks to expand the body of knowledge gained from the past research about the composite repair of sandstone. Different constituent materials were chosen in cases where those previously tested are no longer commercially available or had undesirable effects. In addition, the current research generated data from tests that had been previously unsuccessful. Lastly, this research hopes to provide some explanation for the unexpected results identified in the past research.

2.2.1 Materials

2.2.1.1 *Binders*

The Type I Portland cement used for testing is a fine white powder produced by Lehigh Cement Company and was purchased in November 2004 at George F. Kempf Building Material Supply in Philadelphia. Type I specifications correspond to the requirements of ASTM C150 *Standard Specification for Portland Cement*. Type I Portland cement is "for use when the special properties specified for any other type are not required."[45] The ASTM standard defines Portland cement as:

> a hydraulic cement produced by pulverizing clinker consisting essentially of hydraulic calcium silicates, usually containing one or more of the forms of calcium sulfate as an interground addition.[46]

[45] American Society for the Testing of Materials Standards, "C150-00 Standard Specification for Portland Cement," *Annual Book of ASTM Standards* (West Conshohocken, PA: American Society for Testing and Materials, 2001), 1.
[46] Ibid.

The natural hydraulic lime implemented was manufactured by St. Astier and was purchased from Pennsylvania Lime Works in Milford Square in November 2004. St. Astier natural hydraulic lime was chosen because the hydraulic lime produced by Riverton is no longer commercially available. St. Astier natural hydraulic limes (NHL) are produced from the burning and slaking of a pure chalky limestone with siliceous content with no additions made. According to the manufacturer, they strictly conform to European Norm EN 459 classifying NHL. The limestone in the St. Astier basin derives from crustacean deposits infiltrated by silica but untouched by clay. Feebly hydraulic lime (NHL 2) and moderately hydraulic lime (NHL 3.5) were included in the current testing. Table 5.2 presents a summary of terminology for building limes according to EN 459, and a mineralogical analysis from St. Astier is shown in Table 5.3 below.

Table 2.2: Summary of Terminology for Building Lime according to EN 459

<table>
<tr><td colspan="3">Hydraulic Lime – Setting and hardening in contact with water. Air setting also present. Classified according to Compressive Strength expressed in N/mm^2 measured @ 28 days in mortars prepared with a 1:1.3 binder/sand ration.</td></tr>
<tr><td>OLD</td><td>NEW</td><td>Natural hydraulic lime (NHL)</td></tr>
<tr><td>Eminently Hydraulic</td><td>NHL 5</td><td rowspan="3">NATURAL HYDRAULIC LIMES
Argillaceous or siliceous limestone burned and slaked. Reduced to powder with or without grinding.
NO ADDITIONS ALLOWED</td></tr>
<tr><td>Moderately Hydraulic</td><td>NHL 3.5</td></tr>
<tr><td>Feebly Hydraulic</td><td>NHL 2</td></tr>
<tr><td colspan="3">IF ADDITIONS OF SUITABLE POZZOLANIC OR HYDRAULIC MATERIALS (up to 20%) ARE MADE THE ABOVE PRODUCTS MUST BEAR THE DESIGNATION OF NHL-Z</td></tr>
<tr><td>Artificial Hydraulic Lime</td><td>Hydraulic Limes
HL</td><td>A blend of calcium hydroxide, calcium silicate and calcium aluminates (and possibly other material such as ash, fillers, etc.)</td></tr>
</table>

Table 2.3: St. Astier Mineralogical Analysis

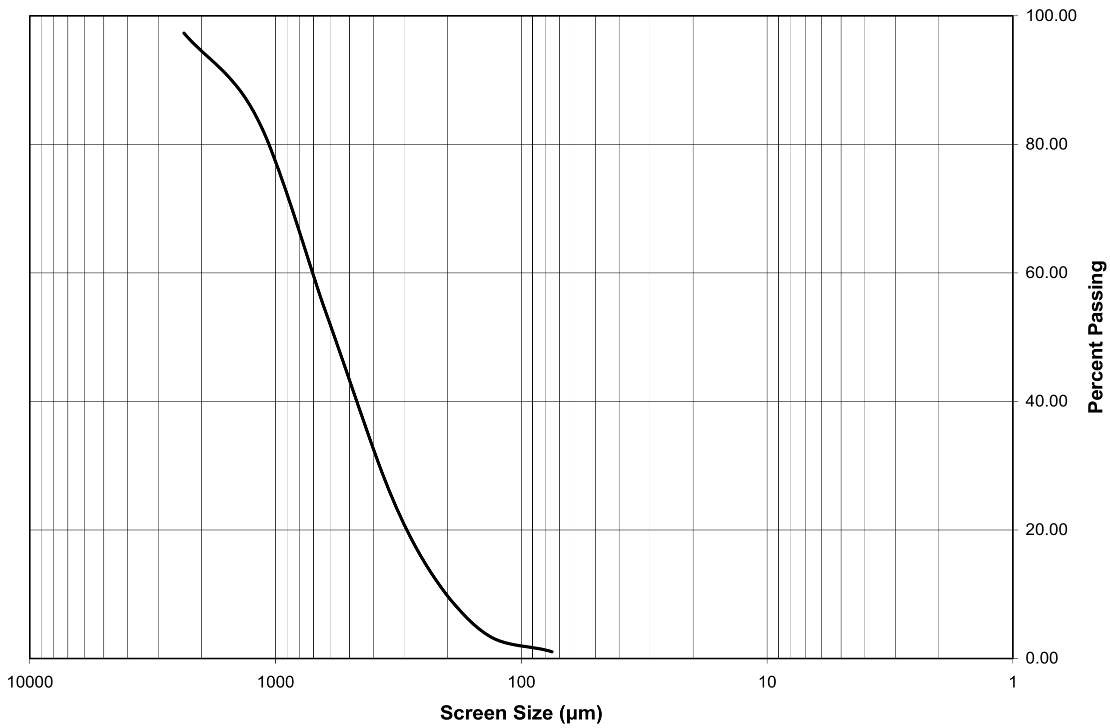
Chemical Compound	Percent	
H_20 (moisture content)	8	
$CaCO_3$	75	*The soluble silica, available to be combined with the CaO produced in the burning of $CaCO_3$, determines the hydraulicity of the finished products.*
SiO_2 (soluble)	11 **reactive/combinable**	
SiO_2 (insoluble)	2 **inert/un-combinable**	
$MgCO_3$	1	

The lime putty used was Niagara Mature Lime Putty manufactured by GenLime, Incorporated and was purchased from Cava Building Supply in Philadelphia in November 2004. Niagara Mature Lime Putty is a high-purity dolomitic lime putty fully slaked and screened for immediate use. The putty is made using dolomitic limestone from a deposit in northwestern Ohio. According to the manufacturer, its chemical composition complies with ASTM C5 *Standard Specification for Quicklime for Structural Purposes* and ASTM C207 *Standard Specification for Hydrated Lime for Masonry Purposes*.

2.2.1.2 *Sand Aggregate*

2.1.1.2 All mortar formulations in the current research were mixed with George Schofield Red Mason Sand #236, purchased in December 2004. The particle size distribution of the sand, illustrated in Graph 2.1 below, was determined according to ASTM C136-01 *Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates*. The sand contains approximately 63% of its mass between 600 and 300 μm in size and has less than one percent fine particles below 75 μm. For use in this research the sand was sieved through a #4 ASTM standard sieve (screen size 4750 μm).

Graph 2.1: Particle Size Distribution of Schofield Sand #236



2.2.1.3 *ACRYLIC ADMIXTURE*

The admixture included in the current testing was Superior Additive 200, an acrylic polymer emulsion manufactured by El Rey Stucco Company, Incorporated and purchased in December 2004. According to the manufacturer, it is for use in Portland cement products, and improves mortars by lowering water absorption rate, improving workability, reducing shrinkage, increasing resistance to freeze/thaw damage, and increasing compressive and flexural strength. Superior Additive 200 is a single component, water based acrylic emulsion that is a milky-white liquid slightly more viscous than water. It has a specific gravity of 1.045 and a solids content of 38% ± 1%. Superior Additive 200, which contains an antifoaming agent, was chosen for this research because the Acryl 60 used in the past research was reported to produce an undesirable air-entraining quality (foaming) to the pure lime putty and hydraulic lime mortars.

2.2.1.3 *Stone*

The current research employed the same Portland, Connecticut brownstone used in previous testing due to its availability in the Architectural Conservation Laboratory. The properties of the stone were measured to evaluate its compatibility with the mortar formulations tested. The data representing the critical properties of the stone from both the past and current research are summarized in section 5.8.

2.2.2 Composite Repair Formulae

As in the past research, all mortar samples were formulated with a binder to sand ratio of 1:3 by volume. However, measuring the volume of relatively small amounts of dry material such as Portland cement or sand was not accurate enough for testing purposes. ASTM C270 specifies the bulk density of Portland cement, hydraulic lime, lime putty, and sand to be used to convert volume proportions to batch weights, which were more easily and accurately measured. The lime putty was strained through cheese cloth to remove excess water. For all mortar formulations, the volume of liquid required to reach the desired consistency was determined, and that volume remained constant for each batch of a given formulation. As a result, the actual volume of Superior Additive 200 differed slightly from formulation to formulation. For the formulations containing Superior Additive 200, a 10% solution was prepared in a volume large enough to be used for all mortar batches to be mixed.

Table 2.4: Repair Mortars and Stone Tested in Current Research

Sample Designation	Proportions (by volume)					
	White Portland Cement	NHL 2	NHL 3.5	Lime Putty	Sand	Acrylic Emulsion
A	1	---	---	2	9	---
B	1	---	---	2	9	10%
C	---	1	---	---	3	---
D	---	1	---	---	3	10%
E	---	---	1	---	3	---
F	---	---	1	---	3	10%
S	Sandstone from the Portland Brownstone Quarries, Connecticut					

2.2.3 PREPARATION

2.2.3.1 *MIXING*

The mortar formulations were mixed according to ASTM C305-00 *Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency* with additional mixing time added. This ensured a uniform procedure for mixing all mortar batches. A Hobart C-100 mixer with three speeds was used for all batches. As stated in the standard, the bowl and paddle were dry prior to mixing every batch. The mixing liquid was placed in the bowl, and the binder(s) was added. The mixer was then started, and mixing proceeded at slow speed (approximately 60 rpm) for 30 seconds. The entire quantity of sand was slowly added over a 30-second period while mixing at slow speed. The mixer was stopped and changed to medium speed (approximately 125 rpm), and mixing resumed for 30 seconds. The mixer was again stopped, and the mortar was let to stand for one and a half minutes. During the first 15 seconds of this interval, any mortar that had collected on the side of the bowl was scraped down into the batch; then for the remainder of this interval, the bowl was covered with plastic wrap. Mixing continued at medium speed for five minutes after which the side of the bowl was scraped down. This step was repeated once. Mixing continued for a final three and one half minutes at medium speed. Total mixing time for all mortar batches was 15 minutes, which was necessary for complete incorporation of the lime binders.

One significant behavior characteristic was observed when mechanically mixing the feebly and moderately hydraulic lime mortars with acrylic emulsion. There was a fine dividing line between the amount of liquid that produced a “damp sand” consistency and the small amount of additional liquid at which the whole mix became very plastic. This threshold was determined by incrementally reducing the amount of liquid until an excessively plastic mix was no longer produced. The resulting “damp sand” consistency was more desirable, and these batches were used to mold all of the hydraulic lime samples with acrylic.

Figure 2.1: Hobart C-100 mixer.

2.2.3.2 *MOLDING*

The molds ranged in size and material according to the requirements of the standard for each test being conducted. Custom-made wood molds were used for the drying shrinkage, thermal expansion, hydric expansion, water absorption, drying index, flexural strength and modulus of elasticity, salt crystallization resistance, and frost resistance tests. Wood molds are preferred for use with lime-based mortars to draw excess water away from the mortar. Polyvinyl chloride (PVC) pipe cut to the proper length was used for the water vapor transmission test. The consistency and setting time tests employed manufactured molds which complied with their respective standard. Wood molds were coated with mineral oil and the PVC molds were coated with petroleum jelly to act as a release agent for ease of mortar sample removal. The molds used for each test are discussed in greater detail in their respective section in Chapter 3.

The molds were filled with fresh mortar in one continuous operation while compacting with a putty knife to encourage the filling of any voids with an additional amount of fresh mortar exceeding the top of the molds in order to achieve a flat surface when scraped off with a putty knife. The top of the molds were scrapped across to remove excess mortar when the mortar had slightly set. All samples, except those used for the consistency, setting time and drying shrinkage tests, were removed from the molds seven days after molding in order to minimize any breaking.

Table 2.5: Mold and Sample Schedule

Test	Standard	Mold Shape	Mold Size	Samples per Formulation	Total Samples
Consistency	ASTM C1437	truncated cone	4” base dia, 2¾“ top dia, 2” depth	2	12
Setting Time	ASTM C191	truncated cone	70 mm base dia, 60 mm top dia, 40 mm depth	3	18
Drying Shrinkage	ASTM 1148	prism	1” x 1” x 6¼” with stud in each end	3	18
Thermal Expansion	ASTM C531	prism	1” x 1” x 6¼” with stud in each end	3	18
Hydric Expansion	RILEM II.7	prism	1” x 1” x 6¼” with stud in each end	same as thermal expansion	---
Water Vapor Transmission	ASTM E 96	cylinder	1½” dia x ½”	3	18
Water Absorption	NORMAL 7/81	cube	2”	3	18
Drying Index	NORMAL 29/88	cube	2”	same as water absorption	---
Flexural Strength & Modulus of Elasticity	ASTM C192	prism	1” x 1” x 4”	3	18
Salt Crystallization Resistance	RILEM V.1b	cube	2”	3	18
Frost Resistance	RILEM V.3	cube	2”	same as drying index	---

2.2.3.3 *Curing*

The curing conditions used follows a variation of the German standard DIN 18-555 recommended in “Lime Mortar: Some Considerations on Testing Standardization.”[47] However, further modification was necessary due to

[47] A. Elena Charola and F.M.A. Henriques, “Lime Mortars: Some Considerations on Testing Standardization,” in *Use of and Need for Preservation Standards in Architectural Conservation,*

environmental constraints. The mortar samples were placed on trays in a baker's rack at room temperature ranging from 70°F to 72°F (21°C to 22°C) with a relative humidity ranging from 30% to 35% for the first seven days. As stated in the section on molding, the samples remained in the molds for this duration, at which time they were removed. The baker's rack was then tented with a clear plastic cover allowing only the bottom of the rack to receive air. The trays were placed in the top half of the rack with one full tray of water placed in the rail directly above and below the sample trays. A hygrometer was placed inside the tent to monitor atmospheric conditions. The temperature ranged from 64°F to 75°F (18°C to 24°C), and the relative humidity ranged from 80% to 90% for 21 days. After the first 28 days, the samples were cured at room temperature ranging from 68°F to 75°F (20°C to 24°C) and relative humidity ranging from 30% to 35% with one wall of the plastic tent completely open to allow for the proper availability of carbon dioxide which is quickly consumed by lime-based mortars. The total curing time for this research was 90 days as opposed to 60 days in the past research. Curing conditions for the samples used to test consistency, setting time, and drying shrinkage were different from those described above and are described in detail in the section for each specific test.

ASTM STP 1355 (West Conshohocken, PA: American Society for Testing and Materials, 1999):145.

Chapter 3 – Performance Testing Program

3.1 Introduction

The current testing program was designed to investigate the critical properties, identified in Chapter One, of the fresh and cured composite repair mortar formulations. The ultimate goal of this testing program was to attain mortar formulations of optimal workability, durability, and compatibility with the Connecticut brownstone. The tests included in this research are by no means exhaustive in the investigation of mortar behavior; however, they address the critical performance properties generally identified for mortar materials. These properties include: consistency, setting time, drying shrinkage, thermal expansion, hydric expansion, water vapor transmission, water absorption, flexural strength and modulus of elasticity, salt crystallization resistance, and frost resistance. The tests were conducted on samples of mortar without sandstone attached.

3.2 Testing Standards

All tests were conducted according to ASTM, NORMAL, and RILEM standardized testing methods. The testing standards were modified as necessary in order to best suit the mortar components being tested, time constraints, and the equipment available.

It is appropriate to note that much literature has been written on the disparity between standards to measure the same or similar material properties.

The disparity is usually in the environmental conditions in which the test is conducted and the units of measurement used to communicate results.[48] These differences make it difficult to compare results across projects and apply the knowledge gained from previous testing programs. In addition, tests for some properties have not been developed for binders like hydraulic limes.

Table 3.1: Standards Consulted for Current Testing Program

Test	Standard	Origin
Consistency	ASTM C1437-99	United States
Setting Time	ASTM C191-99	United States
Drying Shrinkage	ASTM C1148-92a	United States
Thermal Expansion	ASTM C531-00	United States
Hydric Expansion	RILEM II.7	International non-profit association
Water Vapor Transmission	ASTM E96-00	United States
Water Absorption by Total Immersion	NORMAL 7/81	Italy
Drying Index	NORMAL 29/88	Italy
Flexural Strength and Modulus of Elasticity	ASTM C580-98	United States
Salt Crystallization Resistance	RILEM V.1b	International non-profit association
Frost Resistance	RILEM V.3	International non-profit association

3.3 CONSISTENCY

Consistency of the mortars was measured for two reasons: 1) to ensure that samples of the same formulation were uniform from batch to batch, and 2) to determine the effects of Superior Additive 200 on the consistency of the mortars. A target consistency was first established for each mortar formulation by observing the behavior of the mortar in the mixer, on a trowel, and in test repairs. Mortars with an optimal consistency remained on an inverted trowel. The

[48] Amanda Brooke Thomas, *"Study of the Repair Mortars for the Ayyubid City Wall of Cairo,"* (Master's Thesis, University of Pennsylvania, 2004): 34.

consistency test was performed with three samples from the same batch of fresh mortar for each formulation.

3.3.1 ATSM C1437-99: Standard Test Method for Flow of Hydraulic Cement

ASTM C1437-99 requires the measurement of consistency by the use of a flow table conforming to ASTM C230 *Standard Specification for Flow Table for Use in Tests of Hydraulic Cement*. However, the lab was not equipped with a flow table that complied with ASTM C230. Therefore, a device that approximates the specified flow table was used. The flow-table top consists of a piece of plywood covered by a ¼ inch thick piece of Plexiglas. A piece of paper with eight equidistant lines drawn on it according the standard is placed between the plywood and the Plexiglas. A threaded pipe 1 inch in diameter by 5 inches in length is screwed into a 1 inch threaded flange. The flange is attached to the bottom of the plywood table top. A hole approximately 4 inches from the top end of the pipe accommodates a threaded bolt which serves as the lifting handle. The base of the flow table is also a piece of plywood. A threaded pipe 1¼ inches in diameter by 5 inches in length with a 4 inch slot cut through its length is screwed into a 1¼ inch threaded flange. This flange is attached to the base of the table. The smaller pipe fits inside the larger pipe with the lifting handle aligned in the slot. A hose clamp is attached to the larger pipe in order to regulate the height through which the table top can be lifted. The mold used for testing complied with ASTM C230. It is a conical mold of cast bronze with a height of 2 inches, a top opening of 2¾ inches in diameter, and a bottom opening of 4 inches in diameter.

Figure 3.1 Modified flow table and flow mold.

The flow table was clamped securely to the countertop in the lab. The table top was wiped clean and dry, and coated with mineral oil. The flow mold was then placed at the center table top. The mold was filled with fresh mortar in one continuous operation while compacting with a putty knife. The pressure of the knife was just sufficient to ensure uniform filling of the mold. The mortar was cut off to a plane surface, flush with the top of the mold, by drawing the straight edge of a putty knife held nearly perpendicular to the mold with a sawing motion across the top of the mold. The table top was again wiped clean and dry, being careful to remove any water from around the edge of the flow mold. The mold was lifted away from the mortar one minute after completing the molding operation. Immediately, the table was dropped through a height of ½ inch 25 times in 15 seconds. Using a digital caliper, the diameter of each mortar sample was measured along the lines in the table top. The total of the four readings equals the percent increase of the original diameter of the sample.

3.4 Setting Time

The standard test employed measures the depth of penetration of a 1 mm needle at specified time intervals. The test was conducted in order to compare how different binders and the addition of Superior Additive 200 affect setting time. Each mortar formulation was represented by three samples.

3.4.1. ASTM C191-99: Standard Test Method for Time of Setting of Hydraulic Cement by Vicat Needle

The standard requires the samples to be stored in a chamber with a relative humidity of 90% prior to and during the test. This was achieved by placing the samples on trays in a tented baker's rack as described in section 2.2.3.3. Although the standard applies to cement mortars, the lime-based mortars were allowed to set under the same conditions for uniformity.

The procedure used for molding test samples was as follows. Immediately after mixing, the mortar was quickly formed into a ball with gloved hands and tossed six times from one hand to the other while the hands were kept about 6 inches apart. The ball was pressed, while it rested in the palm of one hand, into the larger end of the conical ring mold, held in the other hand, completely filling the mold. The mold was placed on its larger end on a piece of Plexiglas, and the excess mortar was sliced off at the smaller end at the top of the mold by a single oblique stroke of a putty knife held at a slight angle with the top of the mold.

The samples were placed in the storage chamber for 30 minutes after molding. Penetration of the needle was determined at this time and every 15 minutes thereafter until the penetration was zero. Between readings, samples were kept in the tented baker's rack.

Figure 3.2: Vicat apparatus with mortar sample.

For penetration tests, the needle was lowered until it rested on the surface of the mortar. The set screw was tightened and the depth indicator was set at the upper end of the scale. The rod was released by turning the set screw and the needle was allowed to settle for 30 seconds before readings were taken. No penetration test was made closer than ¼ inch from any previous penetration or closer than ⅜ inch from the inside of the mold.

3.5 DRYING SHRINKAGE

3.5.1 ASTM C1148-92A: STANDARD TEST METHOD FOR MEASURING THE DRYING SHRINKAGE OF MASONRY MORTAR

The standard requires the use of test samples conforming to ASTM C490: *Standard Practice for Use of Apparatus for the Determination of Length Change of Hardened Cement Paste, Mortar, and Concrete*. The samples specified are prisms with a section of 1 inch by 1 inch and a length of 11¼ inches with stainless steel gage studs embedded in both ends having a gage length of 10 inches. Gage length is the distance between the ends of the studs embedded inside the sample. The studs are to protrude from each end producing a sample with an overall length of 11⅝ inches. The standard also permits the use of a sample with the same section and an overall length of 6⅝ inches having a gage length of 5 inches. The shorter samples were chosen for this research in order to minimize potential breaking during

Figure 3.3: Climatic control chamber for ASTM C1148.

demolding, curing, and testing. Despite using the shorter size, several samples broke during the demolding process. Both cement/lime putty formulations, with and without acrylic emulsion, were represented by three samples. The feebly hydraulic lime formulations without acrylic and with acrylic were represented by two samples and one sample respectively. The moderately hydraulic lime formulations without acrylic and with acrylic were represented by three samples and one sample respectively. All samples were molded with wood molds equipped to hold the studs properly in place. A 5-inch bar was used to set the gage length. The samples were cured in a storage chamber with a relative humidity of 50% for the duration of the test.

Figure 3.4: Mold conforming to ASTM C490 with studs and gage bar.

This standard also requires the use of a length comparator that complies with ASTM C490. The length comparator measures the length of the test samples relative to a steel reference bar, in this case 6⅝ inches in length. Prior to measuring each sample, the reference bar was placed in the comparator and the apparatus was adjusted until the dial indicator read 0.2000 inches. The samples were then placed immediately in the length comparator and the dial reading was recorded.

The samples were removed from the molds after 48 hours. After 72 hours, the length of the each sample was measured. The length of each sample was again measured at 4, 11, 18, and 25 days after being demolded.

Figure 3.5: Length comparator with reference bar.

Figure 3.6: Measuring sample with length comparator.

3.6 Thermal Expansion

3.6.1 ASTM C531-00: Standard Test Method for Linear Shrinkage and Coefficient of Thermal Expansion of Chemical-Resistant Mortars, Grouts, Monolithic Surfacings, and Polymer Concretes

The standard requires the use of the same sample size with embedded studs according to ASTM C490 as described in section 3.5.1. Each mortar formulation was represented by three samples molded with wood molds that equipped to hold the studs, except for the moderately hydraulic lime formulation. Only one sample of this formulation was tested because the other two broke while curing. The mortar samples were cured for 90 days under conditions mentioned in section 2.2.3.3. Only two stone samples with studs embedded in each end with epoxy were tested for compatibility with the mortar formulations because no more stone was available to be cut.

The samples were first heated to constant length in an oven at 210°F for 16 hours. The samples were then conditioned at 83°F, above the specified 73°F, for 16 hours, and their length was determined by the use of the length comparator described in section 3.5.1. The samples were placed back into the oven at 210°F for 16 hours. Each sample was removed from the oven one at a time at a rate that did not permit the temperature of the oven to drop below 210°F and immediately measured.

3.7 Hydric Expansion

3.7.1 RILEM II.7: Linear Strain Due to Water Absorption

According to the RILEM standard, test samples, if a cylindrical, should have a diameter from 3 cm to 4 cm and a length about 10 cm, and, if prismatic, should have a section from 3 cm^2 to 4 cm^2 and a length about 10 cm. A small glass square with a hemispherical hollow in the center should be glued on to the middle of both ends of each test sample. This test employed the exact same mortar and stone samples used for the thermal expansion test so that they could be measured with the length comparator mentioned in section 3.5.1. It was assumed that conducting the thermal expansion test first would not significantly affect the results of this test.

After curing, the samples were dried in an oven at 60°C to a constant mass. Constant mass was reached when the difference between two consecutive weighings, 24 hours apart, was equal to or less than 0.1% of the mass of the sample. After drying, the samples were placed in a dessicator to cool to room temperature, and their length was measured with the length comparator.

The samples were then placed on glass rods in a plastic container, and the container was filled with deionized water until the samples were completely immersed. Each sample was removed from the water 30 minutes, 1 hour, 2 hours, 4 hours, 8 hours, and 24 hours after immersion, measured, and placed immediately back into the water. The samples were then measured at 24-hour intervals until their length was constant, which was attained after 120 hours. The standard dictates that the measuring device, with the sample in place, remains immersed in water throughout the duration of the test. Following this procedure was not possible due to the number of samples that had to be measured.

3.8 Water Vapor Transmission

Water vapor transmission rate is the steady water vapor movement in unit time through an area with parallel surfaces under specific environmental conditions. Water vapor permeability is the amount of water vapor transmitted through a unit area with parallel surfaces and certain thickness at a unit of time, induced by differences in water vapor pressure at either surface.

3.8.1 ASTM E96-00: Standard Test Methods for Water Vapor Transmission of Materials

This standard requires either a desiccant or wet method be used for determining permeability – the wet method was employed for this research. The sample size used, 12.57cm^2 by 1.3 cm thick, sufficiently fulfilled the specifications of the standard, which dictates a sample be at least five times the sum of the maximum pit depths in both faces. Each mortar formulation was represented by three samples molded from 1½-inch diameter rigid polyvinyl chloride pipe cut to ½ inch in height. The samples were cured for 90 days under conditions mentioned in section 2.2.3.3. Three stone samples of the same size were also tested to determine compatibility with the mortar formulations.

The edge of each sample was wrapped with electrical tape to prevent the transmission of water vapor through this surface. Each sample was then set on the inside ledge of a 50 ml tri-cornered polypropylene beaker which was filled with 30 ml of deionized water according to the specified height of ¾ inch ± ¼ inch from the bottom of the sample. Though not required by the standard, cotton linter was added to the water to prevent any water drops from making contact with the sample. The assembly was then sealed with melted paraffin wax between the edges of the taped sample and the beaker to create an airtight chamber.

Figure 3.7: Climatic control chamber for ASTM E96.

All assemblies were placed in a controlled climatic chamber with a hygrometer to ascertain a constant temperature and relative humidity. Anhydrous calcium sulfate of mesh size eight, manufactured by W.A. Hammond Drierite Company in Ohio, was placed in the bottom of the chamber to maintain the required 50% ± 2% relative humidity. However, the relative humidity inside the chamber fluctuated between 46% and 51%. The temperature within the chamber fluctuated between 28°C and 33°C, while the specified temperature is to be between 20°C and 32°C maintained constant within ± 1°C.

Each assembly was weighed before beginning the test and every 24 hours thereafter for ten days to achieve then data points taken at the same time interval. The electronic scale used had a sensitivity of 0.01 grams.

3.9 WATER ABSORPTION BY TOTAL IMMERSION

Water absorption by total immersion is the amount of water absorbed by the material when fully immersed in deionized water at room temperature. It is expressed as a percentage of the dry weight of the sample. Imbibition capacity is the maximum amount of water absorbed which is determined by proceeding with drying according to NORMAL 29/88 described in section 3.9.2. Apparent porosity is a measure of the fraction of the total volume of a solid that is occupied by pores.

3.9.1 NORMAL 7/81: WATER ABSORPTION BY TOTAL IMMERSION - IMBIBITION CAPACITY

According to the requirements of the NORMAL standard, the sample size, if a cube, should not be smaller than 3 cm or larger than 5 cm for a surface-to-volume ratio between 2 cm and 1.2 cm^{-1}. Each mortar formulation was represented by three samples, and the cube-shaped samples were molded from a 5 cm^3 wood mold. The mortar samples were cured for 90 days under conditions mentioned in section 2.2.3.3. Three 5 cm^3 stone samples were also tested to determine compatibility with the mortar formulations.

After curing, the samples were dried in an oven at 60°C until the difference between two consecutive weighings taken 24 hours apart was less than or equal to 0.1% of the initial weight of the sample. The samples were placed on glass rods in a plastic container, and the container was filled with deionized water until the samples were covered by 2 cm of water. At regular intervals, the samples were removed from the water, blotted with a paper towel to remove excess water, and weighed in air. Weight measurements were taken every 5 minutes for the first hour, every 15 minutes for the next two hours, every hour for the next 5 hours, and after 24 hours. Weighing was then repeated every 24 hours until the asymptotical state was reached – the amount of water absorbed in two successive weighings was less than or equal to 1% of the weight of the sample. The electronic scale used had a sensitivity of 0.01 grams.

At the completion of the test, the samples were weighed hydrostatically; i.e., in water by being suspended from a wire in a beaker with deionized water. Though not required by the NORMAL standard, this measurement allows for an apparent porosity calculation to be made according to ASTM C948-00 *Standard Test Method for Dry and Wet Bulk Density, Water Absorption, and Apparent Porosity of Thin Section of Glass-Fiber Reinforced Concrete*.

Figure 3.8: Hydrostatic weighing.

3.9.2 NORMAL 29/88: Measurement of the Drying Index

The drying index test is conducted in conjunction with NORMAL 7/81 after the samples have been saturated with water at the completion of the test. Excess water was removed from the samples with a damp paper towel one last time prior to weighing, and placed on a non-corrodible tray in a controlled climatic chamber. Anhydrous calcium sulfate was placed at the bottom of the chamber to maintain a relative humidity of 50%. The temperature inside the lab ranged from 25°C to 30°C during the test, above the specified temperature of 20°C ± 1°C. Weight measurements were taken at intervals similar to the total immersion test: every 5 minutes for the first hour, every 15 minutes for the next two hours, after 24 hours, and then every 24 hours until the following equation was true:

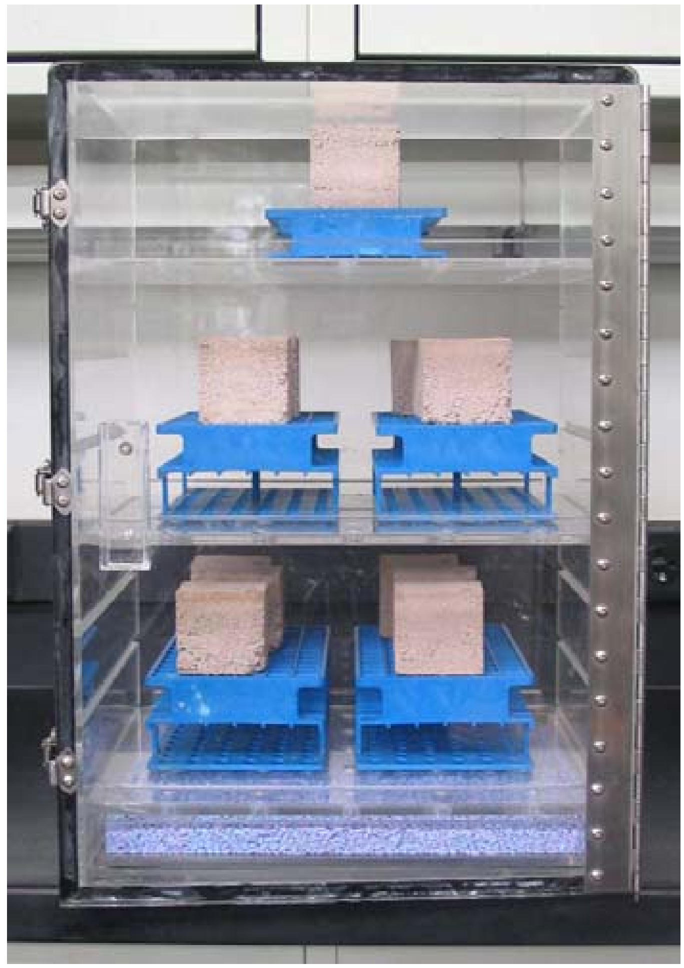


Figure 3.9: Climatic control chamber for NORMAL 29/88

$$1.0 \geq \frac{M_0 - M_{i-1}}{M_0 - M_i} \geq 0.90.$$

The samples were then dried in an oven at 60°C ± 5°C until constant weight was obtained. The weight of each sample was considered to be constant when the difference between two consecutive weighings at 24-hour intervals was less than or equal to 0.01% of the dry weight of the sample.

3.10 Flexural Strength and Modulus of Elasticity

3.10.1 ASTM C580-98: Standard Test Method for Flexural Strength and Modulus of Elasticity of Chemical-Resistant Mortars, Grouts, Monolithic Surfacings, and Polymer Concretes

The sample size used for this test was stipulated in another standard, ASTM C192 *Practice for Making and Curing Concrete Test Specimens in the Laboratory*, which suggested a rectangular beam 4 inches long by 1 inch high by 1 inch wide. Each mortar formulation, shaped from a wood mold, was represented by three samples. Three stones samples of the same size were also tested to determine compatibility with the mortar formulations. The mortar samples were cured for 90 days under conditions mentioned in section 2.2.3.3. Prior to the testing, the depth and width of each test sample was measured near the middle of the sample's length.

The test was conducted at the Laboratory for Research on the Structure of Matter at the University of Pennsylvania using an Instron Testing Machine Model 4206. Each sample was supported at both ends, and a load was applied midway between the supports until the sample was broken (three-point bending). The standard requires the span between supports to be three times the depth of the sample, which in this case was 3 inches. The testing machine was set to produce a cross head speed of 0.01 inch per minute.

Figure 3.10: Instron Model 4206 for flexural test.

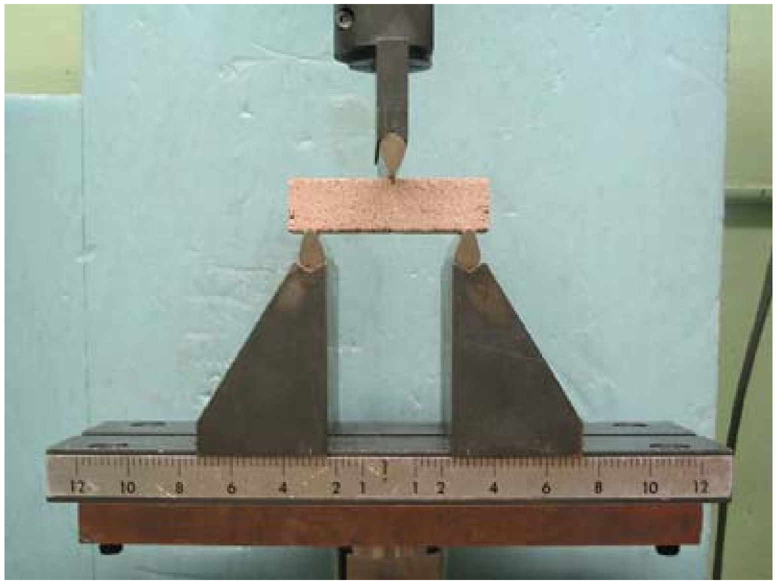


Figure 3.11: Sample in three-point bending.

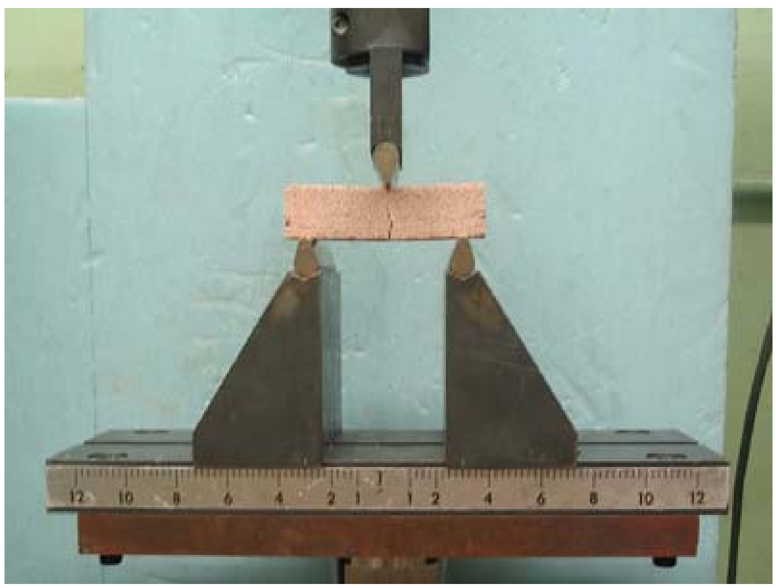


Figure 3.12: Sample in three-point bending after failure.

3.11 Salt Crystallization Resistance

3.11.1 RILEM V.1b: Crystallization Test by Total Immersion (For Treated Stone)

The sample size used for the test is not critical according to the RILEM standard, though a 5 cm cube is recommended, which was employed in this program. Each mortar formulation was represented by three samples, and the cube-shaped samples were molded from a wood mold. The samples were cured for 90 days under conditions mentioned in section 2.2.3.3.

After curing, the samples were dried in an oven at 60°C ± 5°C until the difference between two successive weighings, at a time interval of 24 hours, was not more than 0.1% of the initial weight of the sample. Each sample was photographed to record its initial condition and placed on glass beads inside an 800 ml polypropylene beaker. A 10% solution of Na_2SO_4 was then prepared. The deionized water used to make the solution was tested for sulfates by adding two drops of 2N hydrochloric acid (HCl) and 2 drops of a 10% solution of barium chloride ($BaCl_2$). No white precipitate of barium sulfate ($BaSO_4$) was formed in the test tube which indicated no sulfates were in the water, allowing for a more accurate 10% solution of sodium sulfate. Each beaker was filled with the solution until the samples were covered by at least 2 cm. The samples were immersed in the solution for 2 hours, dried in an oven at 60°C for 20 hours, and cooled to room temperature in a dessicator for 2 hours. This 24-hour test cycle was repeated 15 times. The number of cycles chosen was based on previous research and time constraints. Each sample was weighed and photographed after every second cycle and after the final cycle.

After the final cycle, the salt was removed from the samples by immersing them in frequently refreshed tap water for 7 days. The samples were then dried in an oven at 60°C until constant weight was achieved. The final weight of each sample was measured after cooling to room temperature, and the samples were once again photographed. All weight measurements were taken with an electronic balance with a sensitivity of 0.01 grams.

3.12 Frost Resistance

3.12.1 RILEM V.3: Frost Resistance

The RILEM standard specifies test samples that are cylinders or prisms with a slenderness ratio of at least 4. However, the mortar samples employed in this test were the exact same 5 cm cubes used for the water absorption and drying index tests. Each mortar formulation was represented by three samples, which were cured for 90 days under conditions mentioned in section 2.2.3.3.

The samples were placed in plastic containers with a grid on the bottom to ensure good water and air circulation around the samples. These containers also had holes in the bottom to allow water to drain out when being removed from the water. The samples were initially immersed in water for 6 hours. The succeeding freeze/thaw cycles consisted of 8 hours of freezing in air at -15°C followed by 8 hours of thawing in room temperature tap water with ranged from 20°C to 30°C. The length of freezing and thawing time was chosen for convenience and to maximize the number of cycles due to time constraints. However, the thawing time deviated from the specified 6 hours. The temperature of the thawing water also deviated from the standard which specifies that the thawing water be maintained at 5°C ± 2°C. After thawing, the samples, while still in the container, were lifted from the water and placed back into the freezer. This procedure was employed to minimize disturbance of the samples. The test was conducted for 15 cycles.

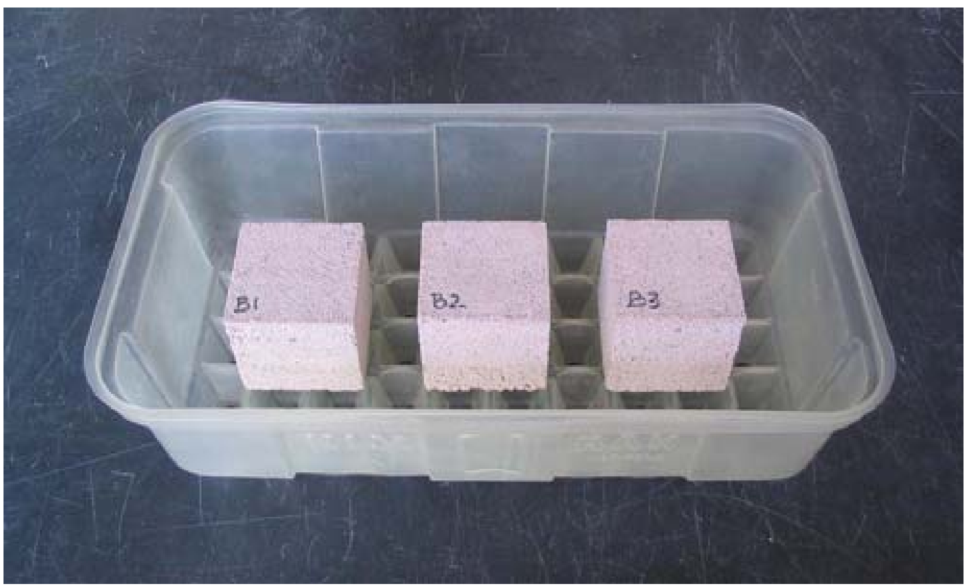


Figure 3.13: Sample container for freeze/thaw test.

After the initial water immersion, at the end of every four cycles, and at the end of the test, the bulk volume of the samples was measured by hydrostatic weighing. This was done by weighing the samples suspended from a wire in water and subtracting that weight from the weight of the sample measured in air after excess water is blotted from the sample. The samples were measured in air using an electronic scale with a sensitivity of 0.01 grams. The samples were also photographed at the time of each weighing. Resistance to freeze/thaw decay is determined by calculating the change in bulk volume expressed as a percentage of the original bulk volume.

CHAPTER 4 – TEST RESULTS

The results of the testing program are presented for each test conducted with tests on the fresh mortar samples represented first, followed by the tests on the cured mortar samples. All tests on cured mortar samples were conducted after 90 days of curing.

4.1 CONSISTENCY ACCORDING TO ASTM C1437-99

A simple inverted trowel test was performed after mixing each batch of mortar to determine workability. Consistency was considered to be optimal when the mortar remained on the inverted trowel. However, all of the fresh mortars tested were too stiff to have a measurable flow. In lieu of flow measurements, the actual mix quantities of the components of each mortar batch by formulation are presented in Table 4.1. The cement/lime putty mortars required less liquid than the hydraulic limes to reach optimal consistency as to be expected. In general, the addition of Superior Additive 200 decreased the amount of total liquid required to achieve optimal consistency for all mortars.

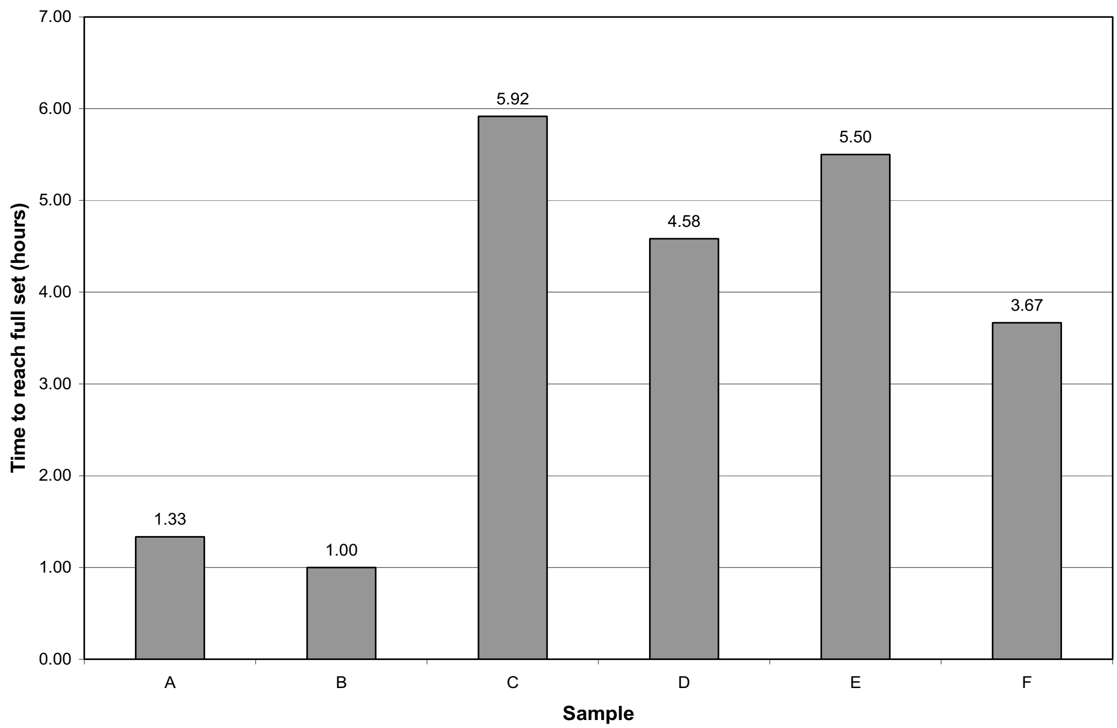
Table 4.1: Mix Quantities by Formulation

Formulation	Component Quantities					
	Portland Cement (g)	Lime Putty (g)	NHL 2 (g)	NHL 3.5 (g)	Sand (g)	Total Liquid (ml)
A	351	597	---	---	2688	190
B	351	597	---	---	2688	180 (10% acrylic)
C	---	---	448	---	2688	460
D	---	---	448	---	2688	410 (10% acrylic)
E	---	---	---	448	2688	460
F	---	---	---	448	2688	390 (10% acrylic)

4.2 Setting Time According to ASTM C191-99

The feebly hydraulic lime mortars took the longest time to set. The moderately hydraulic lime mortars had the next longest setting time, and the cement/lime putty mortars had the shortest setting time. The addition of Superior Additive 200 decreased setting time for all mortars. The results of the setting time test are shown in Graph 4.1. The data collected and setting time graphs for each sample are presented in Appendix B.

Graph 4.1: Average Setting Time



Key to Samples	
Group A	cement/lime putty mortars
Group B	cement/lime putty mortars with acrylic
Group C	feebly hydraulic lime mortars
Group D	feebly hydraulic lime mortars with acrylic
Group E	moderately hydraulic lime mortars
Group F	moderately hydraulic lime mortars with acrylic

4.3 Drying Shrinkage According to ASTM C1148-92a

As expected, all mortar samples steadily decreased in length throughout the entire test. As required by the standard, the percent shrinkage, S, for each sample was calculated as follows:

$$S = [(L_1 - L)/L_0] \times 100$$

where:

L_0 = effective gage length, in.,

L_1 = initial measurement after removal from moist cure, in., and

L = measurement after drying, in.

The effective gage length for all mortar samples was five inches. The values for percent shrinkage of each mortar sample after 25 days of drying in air and the average per sample set are presented in Table 4.2, as required by the standard.

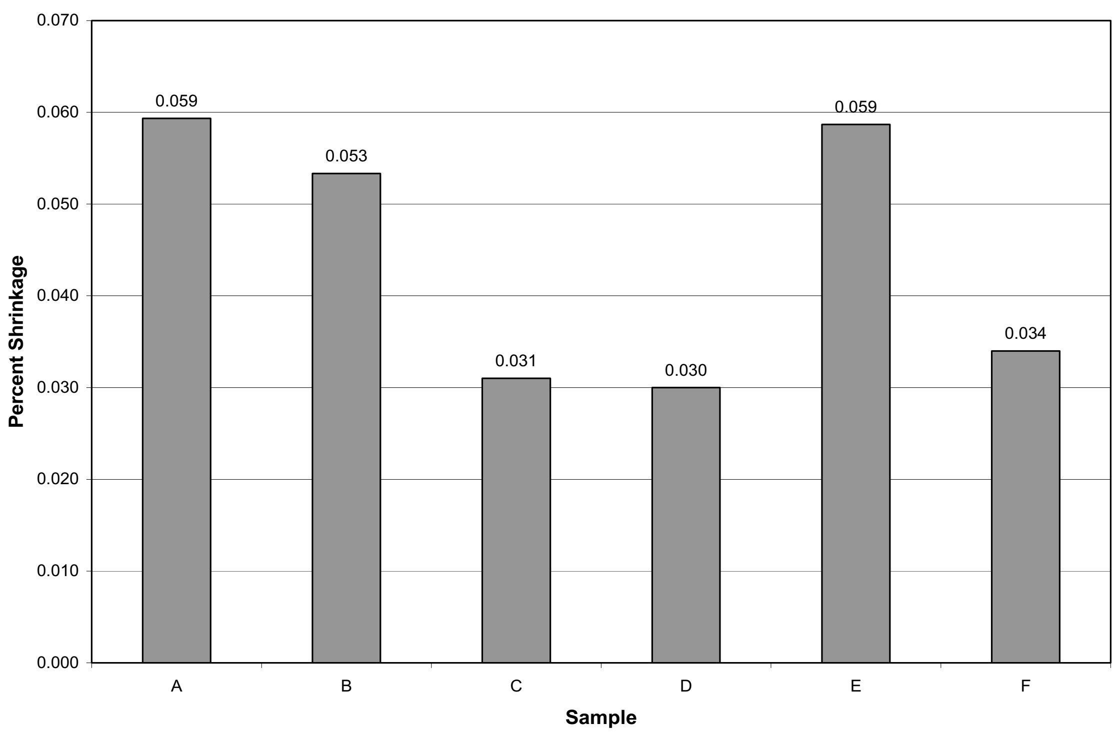
Table 4.2: Drying Shrinkage Calculations

Sample	Initial length, L_1 (in)	Length after drying, L (in)	Percent shrinkage, S	Average percent shrinkage
A1	6.6307	6.6273	0.068	0.059
A2	6.6311	6.6282	0.058	
A3	6.6281	6.6255	0.052	
B1	6.6301	6.6272	0.058	0.053
B2	6.6378	6.6355	0.046	
B3	6.6347	6.6319	0.056	
C1	6.6278	6.6257	0.042	0.031
C2	6.6292	6.6282	0.020	
C3	sample broke when demolded			
D1	6.6296	6.6281	0.030	0.030
D2	sample broke when demolded			
D3	sample broke when demolded			
E1	6.6360	6.6329	0.062	0.059
E2	6.6382	6.6358	0.048	
E3	6.6352	6.6319	0.066	
F1	6.6317	6.6300	0.034	0.034
F2	sample broke when demolded			
F3	sample broke when demolded			

Key to Samples	
Group A	cement/lime putty mortars
Group B	cement/lime putty mortars with acrylic
Group C	feebly hydraulic lime mortars
Group D	feebly hydraulic lime mortars with acrylic
Group E	moderately hydraulic lime mortars
Group F	moderately hydraulic lime mortars with acrylic

The feebly hydraulic lime samples shrank significantly less than both the cement/lime putty and moderately hydraulic lime samples, which exhibited the same percentage of shrinkage. For all mortar samples, the addition of Superior Additive 200 decreased drying shrinkage, significantly only for the moderately hydraulic lime samples. These trends are presented in Graph 4.2 below. However, the drying shrinkage data presented, specifically for the feebly hydraulic and moderately hydraulic lime samples, cannot be considered conclusive due to the number of samples that broke when they were demolded. The data collected and all length calculations are presented in Appendix C.

Graph 4.2: Average Drying Shrinkage



4.4 Thermal Expansion According to ASTM C531-00

The results of the thermal expansion test are expressed in the calculation of the coefficient of thermal expansion, which was done for the mortar samples and the stone samples in order to determine compatibility. The coefficient of thermal expansion, C, of each sample was calculated as follows:

$$C = (Z - Y - W)/T(W - X)$$

where:

Z = length of sample, including studs, at elevated temperature, in.,

Y = length of stud expansion, in., = X x T x k (where k is the coefficient of thermal expansion per °F of the studs),

W = length of sample, including studs, at lower temperature, in.,

T = temperature change, °F and

X = length of the two studs at lower temperature, in.

The elevated temperature for the test was 210°F and the lower temperature was 83°F. The coefficient of thermal expansion of the 316 stainless steel studs used for all calculations was 8.8×10^{-6} in/in·°F.[49] Table 4.3 presents the values for the samples' coefficient of thermal expansion and their averages within the sample sets. The data collected and complete calculations are available in Appendix D.

[49] *ASM Handbook*, 10th ed., vol.1 (Materials Park, OH: ASM International, 1990):871.

Table 4.3: Coefficient of Thermal Expansion Calculations

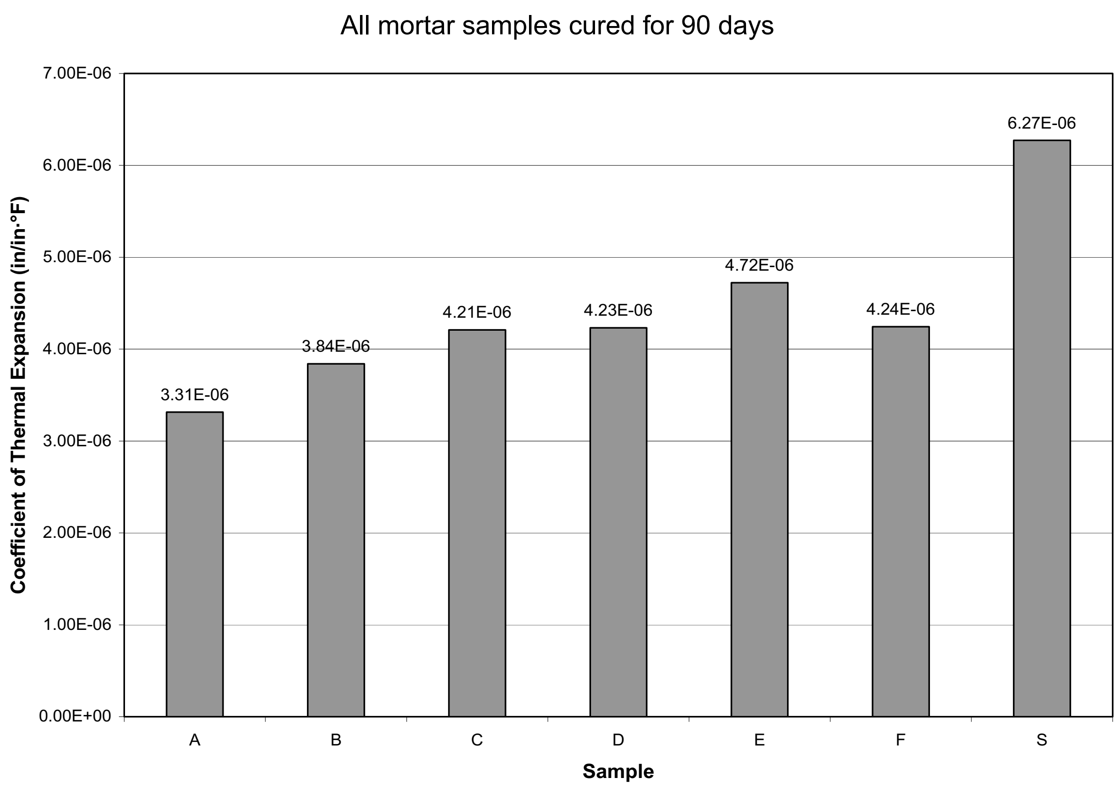
All mortar samples cured for 90 days

Sample	Coefficient of thermal expansion (in/in·°F)	Average CTE
A1	3.57E-06	3.31E-06
A2	2.81E-06	
A3	3.57E-06	
B1	4.04E-06	3.84E-06
B2	3.12E-06	
B3	4.36E-06	
C1	4.21E-06	4.21E-06
C2	sample broke during cure	
C3	sample broke during cure	
D1	3.59E-06	4.23E-06
D2	4.72E-06	
D3	4.38E-06	
E1	5.45E-06	4.72E-06
E2	4.83E-06	
E3	3.89E-06	
F1	4.66E-06	4.24E-06
F2	4.99E-06	
F3	3.09E-06	
S1	6.03E-06	6.27E-06
S2	6.52E-06	
S3	not enough stone available	

Key to Samples	
Group A	cement/lime putty mortars
Group B	cement/lime putty mortars with acrylic
Group C	feebly hydraulic lime mortars
Group D	feebly hydraulic lime mortars with acrylic
Group E	moderately hydraulic lime mortars
Group F	moderately hydraulic lime mortars with acrylic
Group S	Connecticut brownstone

The moderately hydraulic lime mortars exhibited the highest coefficient of thermal expansion, followed by the feebly hydraulic lime mortars and lastly by the cement/lime putty mortars. Superior Additive 200 increased the coefficient of thermal expansion of the cement/lime putty samples and the feebly hydraulic lime samples, but decreased the coefficient of thermal expansion of the moderately hydraulic samples. All mortars exhibited a significantly lower coefficient of thermal expansion than the stone, as illustrated in Graph 4.3. The thermal expansion values for sample Group C and S are somewhat inconclusive because fewer samples were used to calculate their averages.

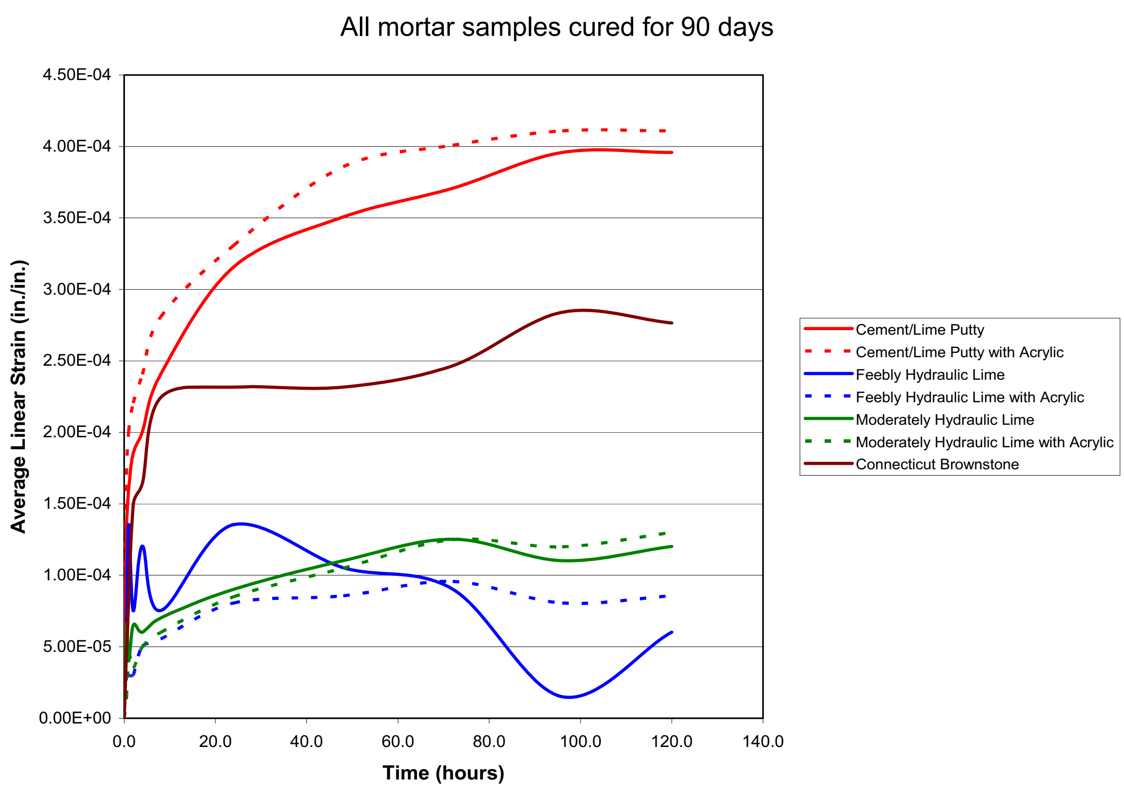
Graph 4.3: Average Coefficient of Thermal Expansion



4.5 Hydric Expansion According to RILEM II.7

The swelling of all mortar and stone samples reached stabilization after 120 hours. All mortars, except for the feebly hydraulic lime mortar, and the stone exhibited a general trend of length increase throughout the test with some fluctuations. The feebly hydraulic lime mortar, represented by only one sample, increased to its maximum length during the first 24 hours and then generally decreased in length for the duration of the test with some significant fluctuations. The length of all samples increased more rapidly during the first 8 hours of the test. Graph 4.4 below presents the averages for each sample set. As previously mentioned, the stone was represented by only two samples.

Graph 4.4: Average Linear Strain Curves



The RILEM standard defines linear strain as the quotient of the length increase of the test sample due to water absorption by the length of the dry sample. The linear strain, ε, of each sample was calculated as follows:

$$\varepsilon = (L_1 - L_0)/l_0$$

where:

L_1 = length comparator reading at 120 hours, in.,

L_0 = initial length comparator reading, in.,

l_0 = initial length of test sample, in.

Table 4.4 presents the values for the samples' linear strain the averages within the sample sets. The data collected and linear strain curves for each sample are presented in Appendix E.

Table 4.4: Linear Strain Calculations

All mortar samples cured for 90 days

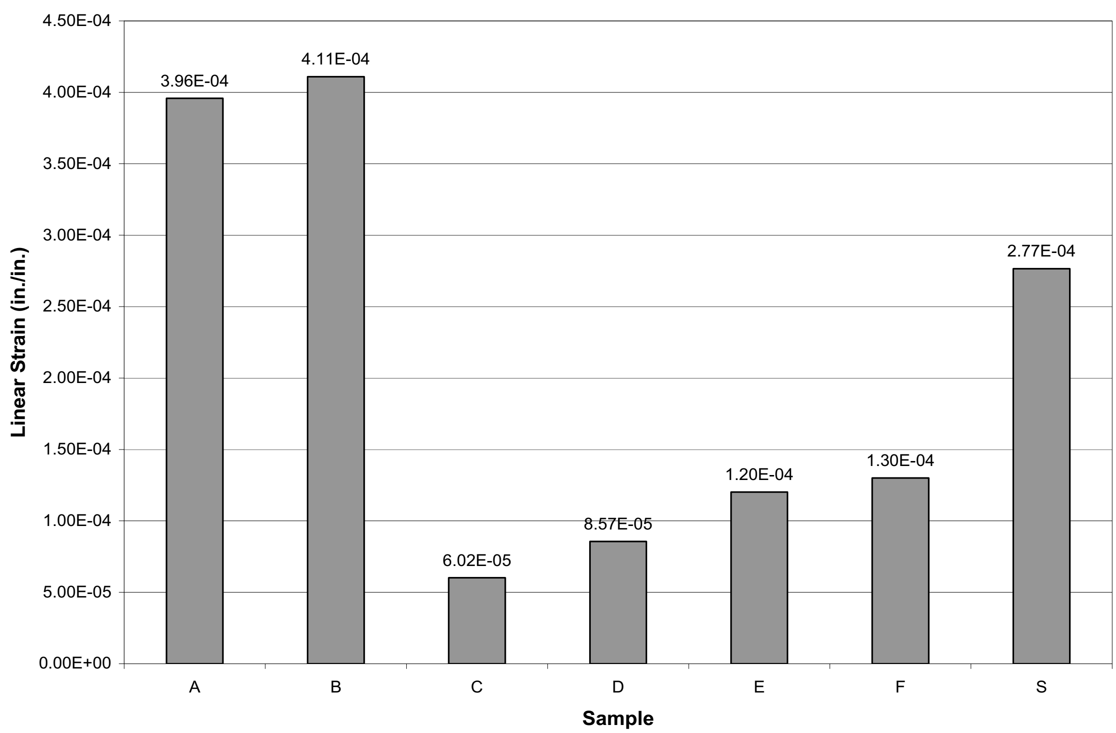
Sample	Reading at 120 hours, L_1	Initial reading, L_0	Initial length, l_0 (in)	Strain, ε (in/in)	Average strain
A1	0.2439	0.2413	6.6663	3.90E-04	3.96E-04
A2	0.2050	0.2022	6.6272	4.22E-04	
A3	0.2393	0.2368	6.6618	3.75E-04	
B1	0.2379	0.2349	6.6599	4.50E-04	4.11E-04
B2	0.2106	0.2081	6.6331	3.77E-04	
B3	0.2319	0.2292	6.6542	4.06E-04	
C1	0.2193	0.2189	6.6439	6.02E-05	6.02E-05
C2	sample broke during cure				
C3	sample broke during cure				
D1	0.2071	0.2068	6.6318	4.52E-05	8.57E-05
D2	0.1820	0.1814	6.6064	9.08E-05	
D3	0.1900	0.1892	6.6142	1.21E-04	
E1	0.2360	0.2357	6.6607	4.50E-05	1.20E-04
E2	0.2286	0.2274	6.6524	1.80E-04	
E3	0.2256	0.2247	6.6497	1.35E-04	
F1	0.2461	0.2454	6.6704	1.05E-04	1.30E-04
F2	0.2258	0.2248	6.6498	1.50E-04	
F3	0.2594	0.2585	6.6835	1.35E-04	
S1	0.2770	0.2752	6.7002	2.69E-04	2.77E-04
S2	0.2549	0.2530	6.6780	2.84E-04	
S3	not enough stone available				

Key to Samples	
Group A	cement/lime putty mortars
Group B	cement/lime putty mortars with acrylic
Group C	feebly hydraulic lime mortars
Group D	feebly hydraulic lime mortars with acrylic
Group E	moderately hydraulic lime mortars
Group F	moderately hydraulic lime mortars with acrylic
Group S	Connecticut brownstone

After 120 hours, the cement/lime putty samples had the highest linear strain, followed by the feebly hydraulic lime and lastly, by the moderately hydraulic lime. The linear strain of all mortars was increased by the addition of Superior Additive 200, though significantly only for the feebly hydraulic lime. The stone exhibited a linear strain higher than both hydraulic lime samples, but lower than the cement/lime putty samples. These results are presented in Graph 4.5 below. Because the same samples were used for both the thermal and hydric expansion tests, the linear strain values for sample Group C and S are somewhat inconclusive.

Graph 4.5: Average Linear Strain

All mortar samples cured for 90 days

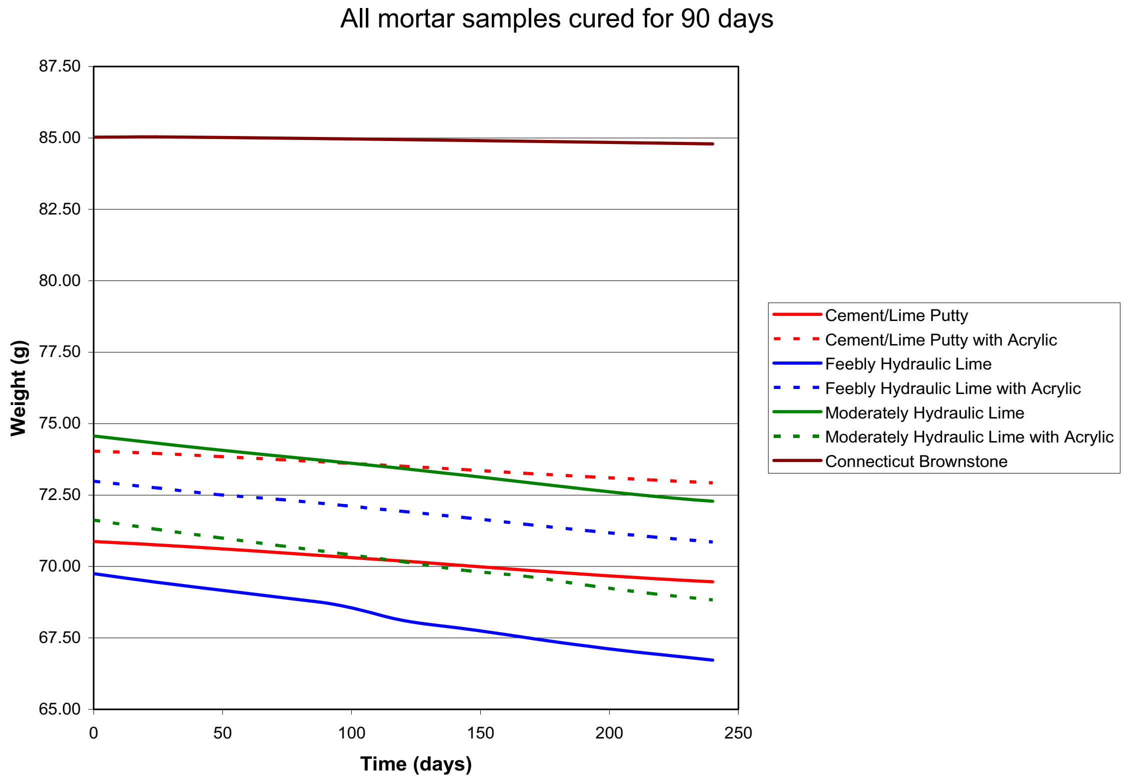


4.6 WATER VAPOR TRANSMISSION ACCORDING TO ASTM E96-00

All mortars and the stone achieved a nominally steady state, dictated by the standard, as the water vapor transmission curve tends toward a straight line with at least six evenly spaced points. By the completion of the test at day 10 a sufficient number of points were achieved by all samples.

The averages for each sample set are presented in Graph 4.6 below. All mortar samples exhibited a weight loss throughout the entire test. The curve for the feebly hydraulic lime formulation shows a rate increase from the fourth day to the fifth day because the C2 sample assembly was tipped over during weight measurement on day five. In addition, the seal on sample F2 broke during the seventh day, and the sample was eliminated from testing at that point. All of the stone samples exhibited a slight initial weight gain until they decreased for the first time on the second day. The data collected and all sample curves are available in Appendix F.

Graph 4.6: Average Water Vapor Transmission Curves



Water vapor transmission, WVT, was calculated in metric units as follows:

$$WVT = G/tA = (G/t)/A$$

where:

G = weight change (from straight line), g,

t = time, h,

G/t = slope of the straight line, g/h,

A = test area (sample area), m^2, and

WVT = water vapor transmission, $g/h \cdot m^2$.

Permeance was calculated in metric units as follows:

$$\text{Permeance} = WVT/S(R_1 - R_2)$$

where:

S = saturation vapor pressure at test temperature, mm Hg (1.333×10^2 Pa)

R_1 = relative humidity at the source expressed as a fraction (in the dish for water method), and

R_2 = relative humidity at vapor sink expressed as a fraction (in the chamber for water method).

Average permeability (metric perm-cm) was calculated as follows:

$$\text{Average permeability} = \text{permeance} \times \text{thickness.}$$

The test area of all mortar and stone samples was 0.013 m^2, which had a thickness of 1.3 cm. The saturation vapor pressure at the test temperature of 31°C was 33.72 mm Hg (4495 Pa).[50] The relative humidity in the dish was 100% (1.0), and in the chamber it was 50% (0.50). Table 4.5 presents the values for the samples' water vapor transmission, permeance, and permeability and their averages within the sample sets, as required by the standard.

[50] *Handbook of Chemistry and Physics*, 74th ed. (Boca Raton, FL: CRC Press, 1994-95):6-15.

Table 4.5: Water Vapor Transmission, Permeance and Permeability Calculations

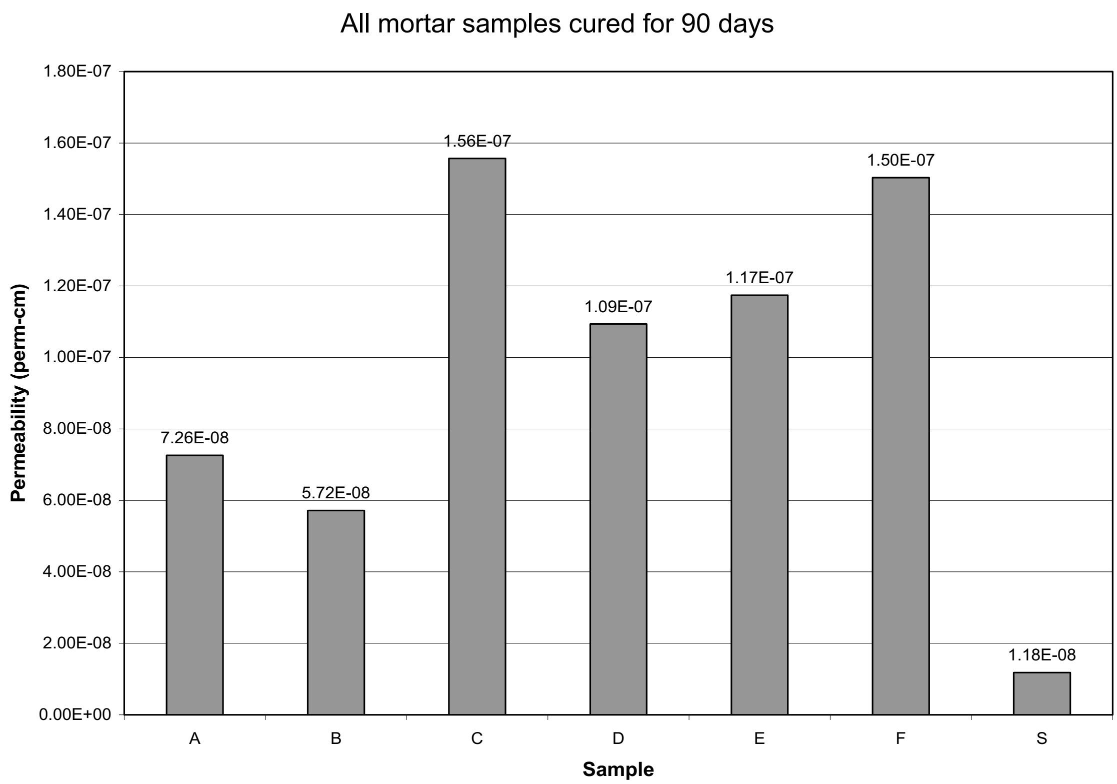
All mortar samples cured for 90 days

Sample	WVT ($g/h \cdot m^2$)	Average WVT	Permeance ($g/Pa \cdot s \cdot m^2$)	Average Permeance	Permeability (perm-cm)	Average Permeability
A1	0.45	0.45	5.55E-08	5.59E-08	7.21E-08	7.26E-08
A2	0.44		5.47E-08		7.11E-08	
A3	0.46		5.74E-08		7.47E-08	
B1	0.43	0.36	5.27E-08	4.40E-08	6.85E-08	5.72E-08
B2	0.34		4.16E-08		5.41E-08	
B3	0.30		3.76E-08		4.89E-08	
C1	1.12	0.97	1.38E-07	1.20E-07	1.80E-07	1.56E-07
C2	0.97		1.20E-07		1.56E-07	
C3	0.82		1.01E-07		1.31E-07	
D1	0.69	0.68	8.48E-08	8.41E-08	1.10E-07	1.09E-07
D2	0.62		7.64E-08		9.94E-08	
D3	0.74		9.11E-08		1.18E-07	
E1	0.72	0.73	8.95E-08	9.03E-08	1.16E-07	1.17E-07
E2	0.70		8.64E-08		1.12E-07	
E3	0.77		9.51E-08		1.24E-07	
F1	0.90	0.94	1.11E-07	1.16E-07	1.44E-07	1.50E-07
F2	0.97		1.19E-07		1.55E-07	
F3	0.94		1.16E-07		1.51E-07	
S1	0.07	0.07	8.71E-09	9.11E-09	1.13E-08	1.18E-08
S2	0.09		1.11E-08		1.44E-08	
S3	0.06		7.53E-09		9.78E-09	

Key to Samples	
Group A	cement/lime putty mortars
Group B	cement/lime putty mortars with acrylic
Group C	feebly hydraulic lime mortars
Group D	feebly hydraulic lime mortars with acrylic
Group E	moderately hydraulic lime mortars
Group F	moderately hydraulic lime mortars with acrylic
Group S	Connecticut brownstone

As indicated in Table 4.5, the cement/lime putty samples had a lower water vapor transmission, permeance, and permeability than both the feebly hydraulic and moderately hydraulic lime samples. The feebly hydraulic lime had the highest water vapor transmission, permeance, and permeability, though only by a negligible amount in relation to the moderately hydraulic lime. The addition of Superior Additive 200 decreased water vapor transmission, permeance, and permeability for the cement/lime putty and feebly hydraulic lime samples and increased these values for the moderately hydraulic lime. All mortar samples, with and without Superior Additive 200, had significantly greater water vapor transmission, permeance, and permeability than the stone. These trends are illustrated by the average permeability of the mortar and stone samples sets in Graph 4.7.

Graph 4.7: Average Permeability



4.7 Water Absorption by Total Immersion According to NORMAL 7/81

All mortars and the stone achieved a nominally steady state, dictated by the standard, as the amount of water in two successive weighings being less than or equal to 1% of the dry weight of the sample. This occurred at the fourth day of weighing for all mortar samples and at the seventh day for the stone.

As illustrated in Graph 4.8, the moderately hydraulic lime mortars absorbed the highest amount of water, followed by the cement/lime putty samples and lastly, by a small amount, the feebly hydraulic lime samples. Superior Additive 200 decreased water absorption of the cement/lime putty samples. However, its addition increased water absorption of the feebly hydraulic and moderately hydraulic limes, though only a negligible amount for the moderately hydraulic lime. All mortar samples, with and without acrylic, absorbed significantly more water than the stone.

Graph 4.8: Average Water Absorption Curves – First 48 Hours

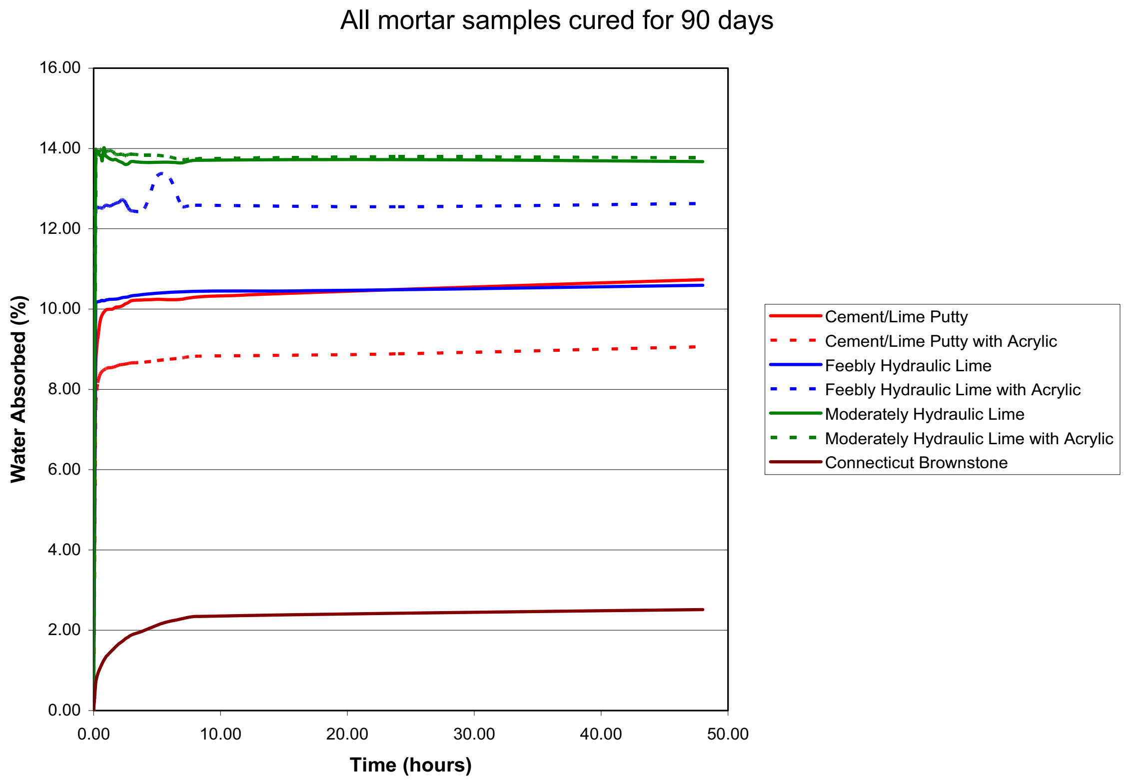


Table 4.6 presents the calculations for the samples' imbibition capacity and apparent porosity and their averages within sample sets. Graph 4.9 below illustrates the imbibition capacity of the mortars and stone showing the highest water absorption capacity, and thus apparent porosity, of the moderately hydraulic lime mortars. The data collected and water absorption curves for each sample are presented in Appendix G.

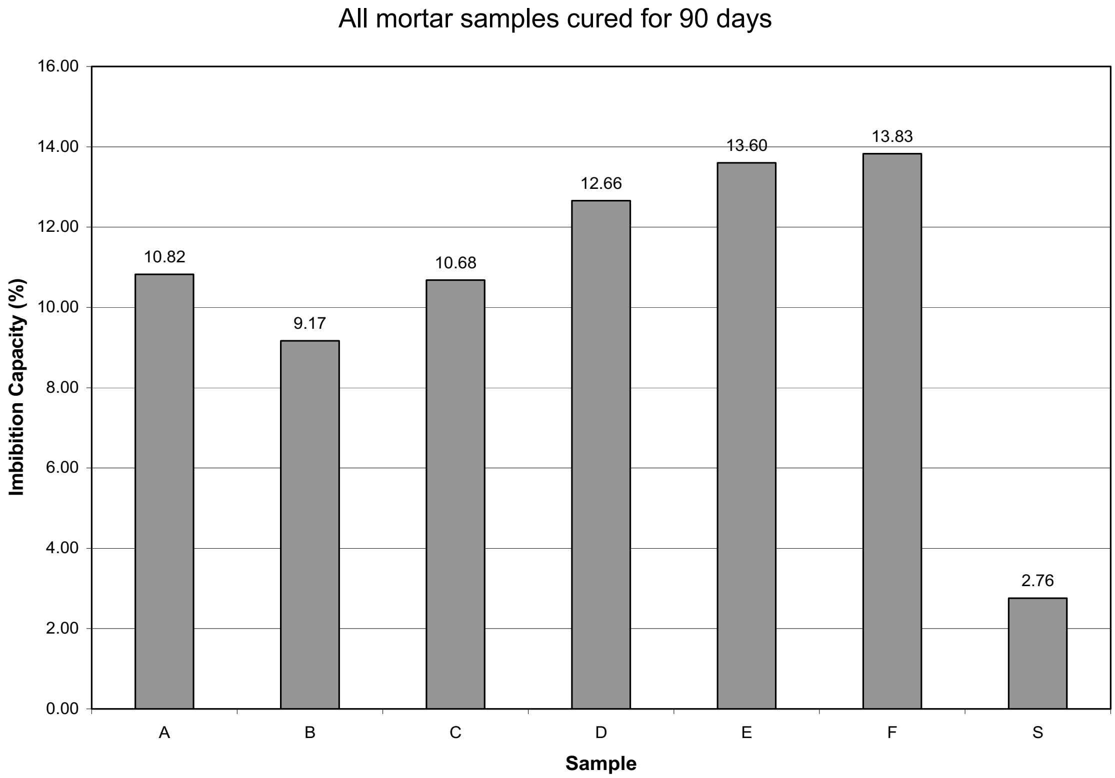
Table 4.6: Imbibition Capacity and Apparent Porosity Calculations

All mortar samples cured for 90 days

Sample	Final weight of water absorption (g)	Hydrostatic weight (g)	Final dry weight (g)	Imbibition capacity (%)	Average imbibition capacity (%)	Apparent porosity %	Average apparent porosity %
A1	262.52	136.54	236.83	10.85		20.39	
A2	269.62	139.79	243.56	10.70	10.82	20.07	20.32
A3	263.39	136.94	237.46	10.92		20.51	
B1	274.78	146.45	252.14	8.98		17.64	
B2	269.60	142.90	246.94	9.18	9.17	17.88	17.89
B3	274.20	144.87	250.75	9.35		18.13	
C1	277.90	148.47	251.00	10.72		20.78	
C2	288.03	155.10	260.63	10.51	10.68	20.61	20.79
C3	277.95	148.69	250.85	10.80		20.97	
D1	255.76	131.24	227.25	12.55		22.90	
D2	261.34	134.06	231.73	12.78	12.66	23.26	23.09
D3	259.03	133.26	229.95	12.65		23.12	
E1	249.39	124.73	219.08	13.84		24.31	
E2	246.09	123.20	216.61	13.61	13.60	23.99	24.03
E3	252.32	127.39	222.59	13.36		23.80	
F1	255.08	126.83	223.87	13.94		24.34	
F2	261.69	132.20	230.77	13.40	13.83	23.88	24.43
F3	265.36	134.19	232.48	14.14		25.07	
S1	318.48	192.68	309.80	2.80		6.90	
S2	320.87	193.84	312.12	2.80	2.76	6.89	6.79
S3	331.87	201.09	323.27	2.66		6.58	

Key to Samples	
Group A	cement/lime putty mortars
Group B	cement/lime putty mortars with acrylic
Group C	feebly hydraulic lime mortars
Group D	feebly hydraulic lime mortars with acrylic
Group E	moderately hydraulic lime mortars
Group F	moderately hydraulic lime mortars with acrylic
Group S	Connecticut brownstone

Graph 4.9: Average Imbibition Capacity

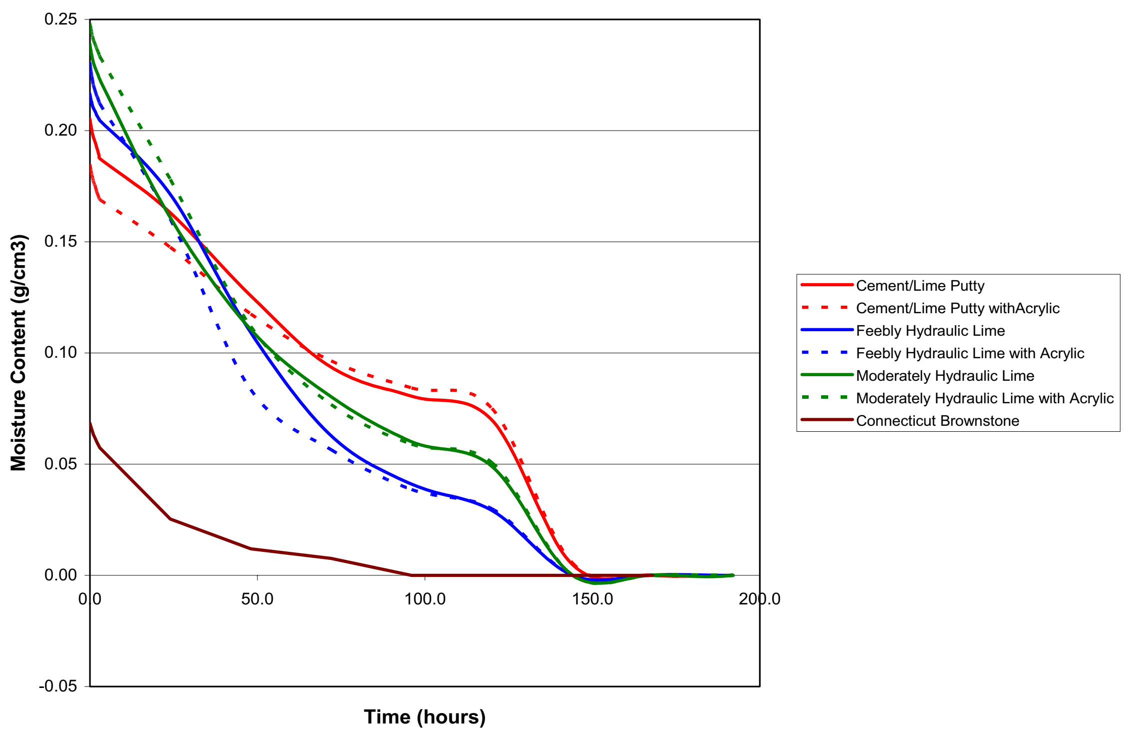


4.8 Drying Curves According to NORMAL 29/88

The rate of drying for the sample sets varied slightly according to the binder. The rate was higher for the feebly hydraulic and moderately hydraulic lime samples and was lower for the cement/lime putty samples. All of the hydraulic lime samples achieved an asymptotical state (0.01% of the weight of the dry sample in two successive weighings) after the seventh day of drying. The cement/lime putty samples achieved an asymptotical state after eight days of drying. The drying rates of the mortar samples were not affected by the addition of Superior Additive 200. The stone reached an asymptotical state after 5 days, indicating a higher rate of drying than all of the mortar samples. The mortar and stone samples declined steadily in weight while in the dessicator, however, there was a sharp decrease after the first day in the oven. The average moisture content as a function of time is illustrated in Graph 4.10. The data collected and drying rate curves for each sample are available in Appendix H.

Graph 4.10: Average Moisture Content during Drying

All mortar samples cured for 90 days



4.9 Flexural Strength and Modulus of Elasticity According to ASTM C580-98

The pound force limit for the mortars did not have to vary according to the binder. All samples were subjected to a 500 pound-force limit with the exception of the first two cement/lime putty samples (A1 and A2) tested at 1,000 pounds to acquire an accurate pound-force limit for the remaining mortar samples. The stone samples were also tested at 500 pounds. There was a three-inch gauge length between the lower bearing blocks for every sample with the upper bearing block in the center which was lowered until fracture.

Flexural strength is equal to the stress calculated at maximum load and was calculated as follows:

$$S = 3\ PL/2\ bd^2$$

where:

S = stress in the sample at midspan, psi,

P = maximum load at or prior to the moment of crack or break, lbf,

L = span, in.,

b = width of sample tested, in., and

d = depth of sample tested, in.

The values for flexural strength and the average per sample set in psi units are presented in Table 4.7. Shaded values had a percent difference from the mean greater than 15% and were eliminated from the final average calculation. ASTM C580 also dictates that if less than two-thirds of the values remain, as with set E, the test should be rerun. However, this was not possible due to limited time and materials. The load-displacement curves for each sample, used to determine both flexural strength and modulus of elasticity, are shown in Appendix I.

Table 4.7: Flexural Strength Calculations

All mortar samples cured for 90 days

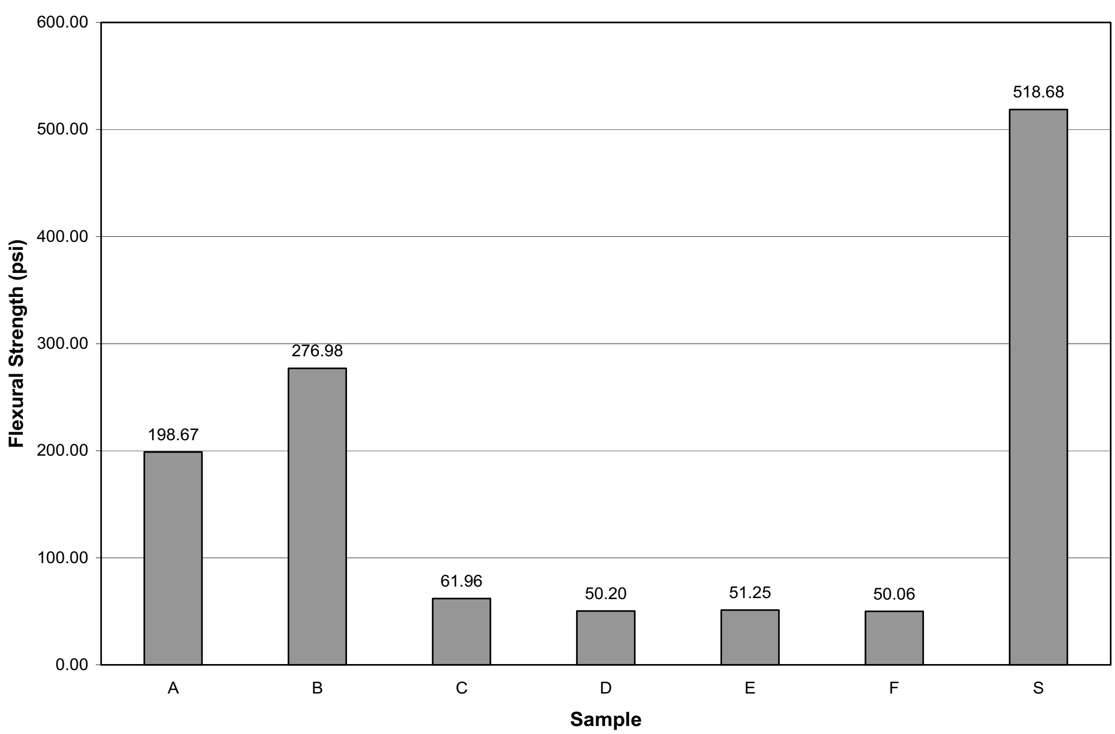
Sample	Maximum load at failure, P (lb)	Span, L (in)	Width of beam, b (in)	Depth of beam, d (in)	Flexural strength, S (psi)	Average flexural strength (psi)
A1	128	3.0	1.017	0.990	193.21	198.67
A2	92	3.0	1.040	0.985	137.46	
A3	132	3.0	1.022	0.974	204.13	
B1	169	3.0	1.026	0.991	251.68	276.98
B2	182	3.0	1.025	0.988	272.52	
B3	216	3.0	1.031	1.013	306.75	
C1	41	3.0	1.022	1.001	60.53	61.96
C2	45	3.0	1.025	1.006	64.36	
C3	42	3.0	1.017	1.012	60.98	
D1	29	3.0	1.003	1.002	43.48	50.20
D2	37	3.0	1.050	0.990	53.91	
D3	36	3.0	1.014	1.005	53.21	
E1	32	3.0	1.024	0.962	51.25	51.25
E2	26	3.0	1.025	0.986	38.70	
E3	36	3.0	1.022	0.946	59.23	
F1	36	3.0	1.038	0.993	52.80	50.06
F2	38	3.0	1.019	0.995	56.11	
F3	28	3.0	1.033	0.998	41.29	
S1	416	3.0	1.044	1.049	542.53	518.68
S2	391	3.0	1.073	0.997	549.24	
S3	366	3.0	1.116	1.029	464.27	

Key to Samples	
Group A	cement/lime putty mortars
Group B	cement/lime putty mortars with acrylic
Group C	feebly hydraulic lime mortars
Group D	feebly hydraulic lime mortars with acrylic
Group E	moderately hydraulic lime mortars
Group F	moderately hydraulic lime mortars with acrylic
Group S	Connecticut brownstone

The cement/lime putty samples exhibited a higher flexural strength than the feebly hydraulic and moderately hydraulic lime binders, with the moderately hydraulic lime samples exhibiting the lowest flexural strength. The addition of Superior Additive 200 increased the flexural strength of the cement/lime putty mortars. Conversely, it decreased the flexural strength of both the feebly hydraulic and moderately hydraulic lime mortars, though by a negligible amount for the moderately hydraulic lime. All mortar samples (with and without acrylic) exhibited a significantly lower flexural strength than that of the stone. A comparison of average flexural strength for each sample set is illustrated in Graph 4.11.

Graph 4.11: Average Flexural Strength

All mortar samples cured for 90 days



Modulus of elasticity is the ratio, within the elastic limit, of stress to corresponding strain. It is determined by drawing a tangent line to the steepest initial portion of the load-deformation curve and calculating as follows:

$$E = L^3 M_1/4\ bd^3$$

where:

E = modulus of elasticity in bending, psi,

L = span, in.,

b = width of sample tested, in.,

d = depth of sample tested, in., and

M_1 = slope of the initial straight-line portion of the load-deflection curve, lbf/in.

The figures for flexural strength and the average per sample set in psi units are presented in Table 4.8. Shaded values had a percent difference from the mean greater than 15% and were eliminated from the final average calculation according to ASTM C580. The standard also dictates that if less than two-thirds of the values remain, as with sample sets A, E, and F, the test should be rerun. However, this was not possible due to limited time and materials.

Table 4.8: Modulus of Elasticity Calculations

All mortar samples cured for 90 days

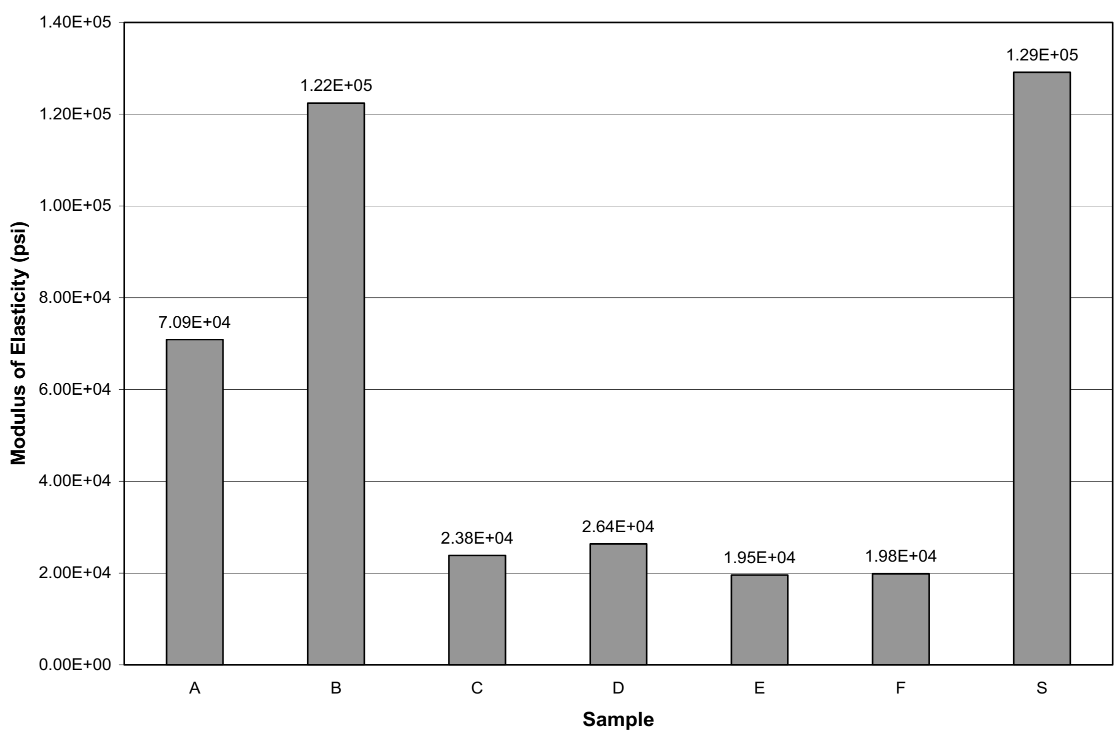
Sample	Span, L (in)	Width of beam, b (in)	Depth of beam, d (in)	Slope, M_1 (lb/in)	Modulus of elasticity, E (psi)	Average modulus of elasticity (psi)
A1	3.00	1.017	0.990	14495	9.92E+04	7.09E+04
A2	3.00	1.040	0.985	10438	7.09E+04	
A3	3.00	1.022	0.974	12162	8.69E+04	
B1	3.00	1.026	0.991	16014	1.08E+05	1.22E+05
B2	3.00	1.025	0.988	20445	1.40E+05	
B3	3.00	1.031	1.013	18950	1.19E+05	
C1	3.00	1.022	1.001	3279	2.16E+04	2.38E+04
C2	3.00	1.025	1.006	3674	2.38E+04	
C3	3.00	1.017	1.012	4082	2.61E+04	
D1	3.00	1.003	1.002	3713	2.48E+04	2.64E+04
D2	3.00	1.050	0.990	4543	3.01E+04	
D3	3.00	1.014	1.005	3677	2.41E+04	
E1	3.00	1.024	0.962	1672	1.24E+04	1.95E+04
E2	3.00	1.025	0.986	2844	1.95E+04	
E3	3.00	1.022	0.946	3389	2.64E+04	
F1	3.00	1.038	0.993	3815	2.53E+04	1.98E+04
F2	3.00	1.019	0.995	2950	1.98E+04	
F3	3.00	1.033	0.998	2261	1.49E+04	
S1	3.00	1.044	1.049	22838	1.28E+05	1.29E+05
S2	3.00	1.073	0.997	15791	1.00E+05	
S3	3.00	1.116	1.029	23481	1.30E+05	

Key to Samples	
Group A	cement/lime putty mortars
Group B	cement/lime putty mortars with acrylic
Group C	feebly hydraulic lime mortars
Group D	feebly hydraulic lime mortars with acrylic
Group E	moderately hydraulic lime mortars
Group F	moderately hydraulic lime mortars with acrylic
Group S	Connecticut brownstone

The results for modulus of elasticity were similar to those for flexural strength. The cement/lime putty samples exhibited a significantly higher modulus of elasticity than the feebly hydraulic and moderately hydraulic lime mortars, with the moderately hydraulic lime samples exhibiting a slightly lower modulus of elasticity than the feebly hydraulic lime. The modulus of elasticity was increased for all mortar samples with the addition of Superior Additive 200, though negligibly for both feebly hydraulic and moderately hydraulic lime. All mortar samples exhibited a significantly lower modulus of elasticity than the stone, except for the cement/lime putty samples with acrylic which were only slightly lower. Graph 4.12 illustrates the average values for modulus of elasticity.

Graph 4.12: Average Modulus of Elasticity

All mortar samples cured for 90 days



4.10 Salt Crystallization Resistance According to RILEM V.1b

All of the mortar samples, except for sample C1, survived all 15 cycles of immersion in 10% sodium sulfate solution. According to the standard, both feebly hydraulic lime mortars, with and without Superior Additive 200, exhibited weight loss. Contrary to the standard, however, all other mortars exhibited weight gain as opposed to weight loss, even after the soaking period at the end of the test. This was probably caused by the migration of the salts in solution into the pores of the mortar, which crystallized during drying in the oven. The repeated cycles may have encouraged the continual growth of salt crystals which accounts for the increase in weight. The addition of Superior Additive 200 did not significantly affect weight loss except in the feebly hydraulic lime samples. The percent weight change calculations are presented in Table 4.9, and the average weight change for each sample set is illustrated in Graph 4.13.

Table 4.9: Salt Crystallization Weight Change Calculations

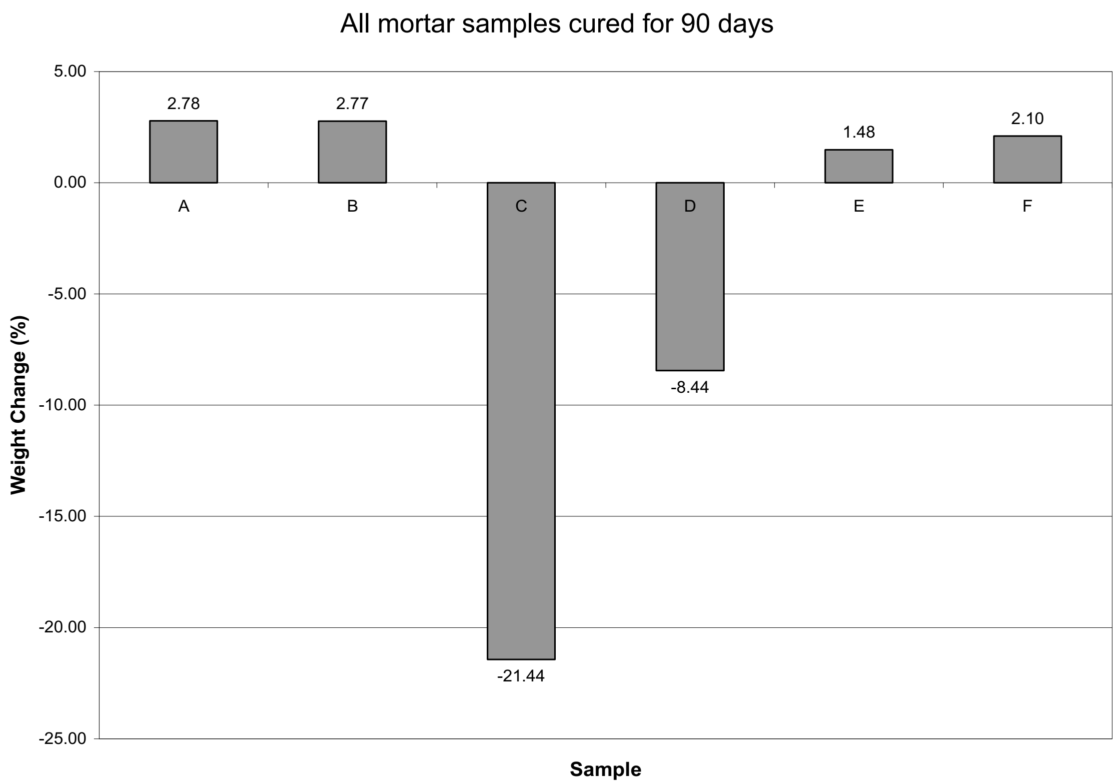
All mortar samples cured for 90 days

Sample	Initial weight (g)	Final weight (g)	Weight change (%)	Average weight change
A1	237.64	243.98	2.67	2.78
A2	239.91	246.55	2.77	
A3	236.35	243.23	2.91	
B1	238.69	245.41	2.82	2.77
B2	230.53	236.38	2.54	
B3	235.84	242.79	2.95	
C1	sample broke during 8th cycle			-21.44
C2	248.88	203.23	-18.34	
C3	248.98	187.91	-24.53	
D1	227.74	207.56	-8.86	-8.44
D2	226.53	205.98	-9.07	
D3	232.03	214.86	-7.40	
E1	233.86	237.80	1.68	1.48
E2	226.12	229.80	1.63	
E3	233.50	236.15	1.13	
F1	232.75	237.62	2.09	2.10
F2	232.42	237.44	2.16	
F3	228.60	233.29	2.05	

Key to Samples

Group A	cement/lime putty mortars
Group B	cement/lime putty mortars with acrylic
Group C	feebly hydraulic lime mortars
Group D	feebly hydraulic lime mortars with acrylic
Group E	moderately hydraulic lime mortars
Group F	moderately hydraulic lime mortars with acrylic
Group S	Connecticut brownstone

Graph 4.13: Average Salt Crystallization Weight Change



The visual appearance of the mortars was recorded and photographed for documentation of material loss or surface erosion (see Appendix J). Both cement/lime putty mortars, with and without Superior Additive 200, exhibited only minor disaggregation at the edges and corners. Both feebly hydraulic lime mortars, with and without Superior Additive 200, exhibited significant erosion of all surfaces. Disaggregation was exhibited to a greater degree in the samples without acrylic emulsion, which also showed significant cracking. The moderately hydraulic lime mortars without Superior Additive 200 exhibited some disaggregation at the edges and corners. The moderately hydraulic lime mortars with acrylic emulsion exhibited little to no erosion through all 15 cycles. The samples subjected to the 15 wet/dry cycles were able to be handled and weighed at the completion of the test.

4.11 Frost Resistance According to RILEM V.3

All of the mortar samples, except for sample E2, survived all 15 freeze/thaw cycles. Sample E2 broke while being weighed after the 12th cycle and was eliminated from the test at that point. The results of the frost resistance test are expressed as the amount of material, the bulk volume, retained throughout the test. The highest percent bulk volume retained corresponds to the highest resistance to freeze/thaw decay.

The cement/lime putty mortar was the most durable, followed by the feebly hydraulic lime, and lastly, by the moderately hydraulic lime. Superior Additive 200 had no effect on the cement/lime samples, but significantly increased the average bulk volume of the moderately hydraulic limes samples and significantly decreased the value of the feebly hydraulic lime samples. It should be noted that the final bulk volume calculated for both cement/lime putty mortars and the moderately hydraulic lime mortar with acrylic emulsion was slightly higher than 100%. This is most likely due to the limited accuracy of the balance used for hydrostatic weighing. The bulk volume calculations are presented in Table 4.10, and the average bulk volume retained after 15 freeze/thaw cycles for each sample set is illustrated in Graph 4.14.

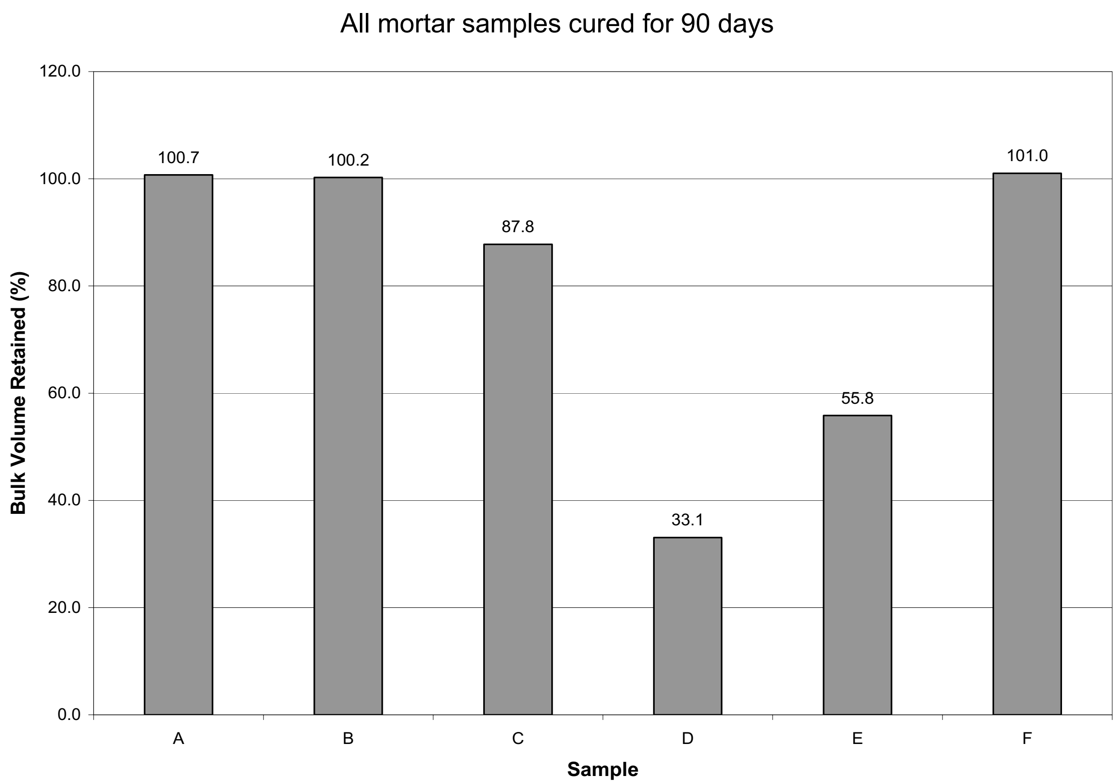
Table 4.10: Bulk Volume Calculations

All mortar samples cured for 90 days

Sample	Initial bulk volume	Final bulk volume	Bulk volume retained (%)	Average bulk volume retained
A1	125.42	127.44	101.61	100.72
A2	128.95	129.72	100.60	
A3	125.86	125.79	99.94	
B1	128.07	128.54	100.37	100.23
B2	126.73	126.81	100.06	
B3	129.07	129.39	100.25	
C1	129.46	112.35	86.78	87.78
C2	132.54	119.39	90.08	
C3	128.76	111.35	86.48	
D1	123.21	45.57	36.99	33.06
D2	126.07	37.36	29.63	
D3	124.92	40.67	32.56	
E1	123.84	60.02	48.47	55.84
E2	sample broke during 12th cycle			
E3	123.99	78.38	63.21	
F1	128.51	127.55	99.25	101.00
F2	128.95	132.06	102.41	
F3	130.91	132.64	101.32	

Key to Samples	
Group A	cement/lime putty mortars
Group B	cement/lime putty mortars with acrylic
Group C	feebly hydraulic lime mortars
Group D	feebly hydraulic lime mortars with acrylic
Group E	moderately hydraulic lime mortars
Group F	moderately hydraulic lime mortars with acrylic
Group S	Connecticut brownstone

Graph 4.14: Average Bulk Volume Retained



The visual appearance of the mortars was recorded and photographed for documentation of material loss or surface erosion (see Appendix K). Both cement/lime putty mortars, with and without Superior Additive 200, exhibited little to no disaggregation at the edges and corners. Both feebly hydraulic lime mortars, with and without Superior Additive 200, exhibited significant erosion of all surfaces, though to a much greater degree in the samples with acrylic emulsion. The moderately hydraulic lime mortars without Superior Additive 200 also exhibited severe erosion. Though the addition of the acrylic emulsion increased the bulk density of the moderately hydraulic lime mortar significantly, all three samples broke along horizontal lines while being weighed at the end of the test.

CHAPTER 5 – DISCUSSION OF RESULTS AND CONCLUSIONS

The individual properties tested for the composite repair mortars say much about their independent behavior. When attempting to understand how a masonry system will work as a whole, the results of the tests on the mortars are more revealing relative to the same properties tested for the Connecticut brownstone. A discussion will follow on the properties of the mortars – both in a fresh and cured state – independent of the sandstone in an effort to determine the effects of Superior Additive 200. For every property, the results for the mortars without acrylic emulsion will be discussed first followed by the effects of the acrylic emulsion. Additionally, the discussion will attempt to compare the results of the mortar tests with the results of the tests conducted on the stone. The ideal performance properties of a composite repair mortar independent of and compared to the stone are ranked in descending order of importance in Table 5.1, which should be used a guide when reviewing all test results.

Table 5.1: Ideal Performance Properties for Composite Repair

Property	Independent of Stone	Compared to Stone
1. Water Vapor Transmission (Permeability)	high	higher
2. Water Absorption (Porosity)	high	higher
3. Water Evaporation Rate	high	higher
4. Flexural Strength	high	lower
5. Modulus of Elasticity	low	lower
6. Drying Shrinkage	low	---
7. Hydric Expansion	low	equal
8. Thermal Expansion	low	equal
9. Salt Crystallization Resistance	high	lower
10. Freeze/Thaw Resistance	high	lower
11. Setting Time	moderate	---
12. Consistency	good workability	---

5.1 Fresh Mortars

The properties of fresh composite repair mortars are significant and unavoidably related. Consistency is important because the mortar must be plastic enough to be pushed into the area being filled, yet stiff enough to stay where it is applied long enough to set. Setting time is important because the mortar must not dry and shrink too rapidly. Drying shrinkage is important because the mortar must have minimal shrinkage as it cures to prevent cracking and stone interface separation. Cracks in the repair will allow the entry of water accelerating the decay of the repair and the surrounding stone, and they are unsightly. In addition to these properties, determining an appropriate composite repair mortar will depend heavily on environmental conditions; for example, low versus high relative humidity.

5.1.1 Consistency

Though all of the mortars were too stiff to have a measurable flow, it was still possible to assess the effect of Superior Additive 200. This was done by comparing the total amount of liquid required to achieve optimal consistency between mortars with the same components and proportions – one with and one without the acrylic emulsion. In every case, Superior Additive 200 reduced the total amount of liquid required to achieve optimal consistency: by 5% (from 190 ml to 180 ml) for the cement/lime putty mortars, 11% (from 460 ml to 410 ml) for the feebly hydraulic lime mortars, and 15% (from 460 ml to 390 ml) for the moderately hydraulic lime mortars. Published research shows similar results with acrylic polymers in concretes and Portland cement mortars attributed to the lubricating properties of the acrylic emulsions.[51] The colloidal particles in the acrylic emulsion act like ball bearings to increase the lubricity of the mortar. This is significant because the amount of water added to mortar affects the amount of shrinkage it will undergo as it dries; adding more water during mixing results in more potential shrinkage during cure.[52] Since the addition of Superior Additive 200 reduced the total amount of liquid needed to achieve optimal consistency, it should decrease drying shrinkage (see section 5.1.3).

[51] Yoshihiko Ohama and V.S. Ramachandran, “Polymer-Modified Mortars and Concretes,” in Concrete Admixtures Handbook: Properties, Science, and Technology, ed. V.S. Ramachandran (Park Ridge, NJ: Noyes Publications, 1995), 583.
[52] Hill and David, 177.

5.1.2 Setting Time

As expected, the average setting time of the cement/lime putty mortars was 78% shorter than that of the feebly hydraulic lime and 76% shorter than the moderately hydraulic lime. The addition of Superior Additive 200 decreased the average setting time for all mortars: by 25% (from 1.3 to 1.0 hours) for the cement/lime putty mortars, 23% (from 5.9 to 4.6 hours) for the feebly hydraulic lime mortars, and 33% (from 5.5 to 3.7 hours) for the moderately hydraulic lime mortars. Shorter setting time is an advantage if the surface of the repair is to be tooled, etched, or left unprotected.

5.1.3 Drying Shrinkage

The average percent drying shrinkage of the feebly hydraulic lime mortars was approximately half that of both the cement/lime mortars and moderately hydraulic lime (average percent drying shrinkage was: 0.031%, 0.059%, and 0.059% respectively). As mentioned in section 5.1.1, the addition of Superior Additive 200 should have decreased drying shrinkage. This occurred for all mortar samples, but significantly only for the moderately hydraulic lime. The percent drying shrinkage of the cement/lime mortars decreased to 0.053%, the feebly hydraulic lime decreased to 0.030%, and the moderately hydraulic lime to 0.034%. Therefore, the moderately hydraulic lime mortar with acrylic emulsion exhibits the lowest potential for cracking during cure. However, as mentioned in section 4.3, the drying shrinkage results are not definitive due to the number of samples that broke when they were demolded.

5.2 EXPANSION

Composite repair mortars must be dimensionally stable in response to fluctuations in temperature and moisture content. Repairs that exhibit excessive expansion and contraction will likely crack accelerating decay. Additionally, the repair must have expansion and contraction properties similar to that of the surrounding stone. Dissimilar movement will result in damage to the stone, cracking of the repair, or premature weakening of their bond. The results of the thermal expansion and hydric expansion tests are discussed below. As mentioned in sections 4.4 and 4.5, the result of these tests are not definitive with respect to the feebly hydraulic lime mortars without acrylic emulsion and the Connecticut brownstone because they were represented by only one sample and two samples respectively.

5.2.1 THERMAL EXPANSION

The average coefficient of thermal expansion of the feebly hydraulic lime was 12% higher than that of the moderately hydraulic lime mortars and 43% higher than cement/lime putty mortars (average coefficient of thermal expansion was: 4.72×10^{-6} in/in·°F, 4.21×10^{-6} in/in·°F, and 3.31×10^{-6} in/in·°F respectively). The effect of Superior Additive 200 was inconsistent. Its addition increased the coefficient of thermal expansion of the cement/lime putty mortars by 16% (3.84×10^{-6} in/in·°F). With acrylic emulsion the value of the feebly hydraulic lime remained virtually unchanged (4.23×10^{-6} in/in·°F), and the moderately hydraulic lime decreased by 10% (4.24×10^{-6} in/in·°F). The sandstone tested exhibited the highest coefficient of thermal expansion (6.27 x 10^{-6} in/in·°F), which was 33% higher than that of the moderately hydraulic lime mortar without acrylic emulsion. Therefore, the thermal expansion data suggests that the moderately hydraulic lime mortar without acrylic emulsion would be the most appropriate composite repair mortar because it is most compatible with the sandstone and its coefficient is not significantly higher than the other mortars.

5.2.2 Hydric Expansion

The linear strain due to water absorption of the cement/lime putty mortar was approximately two and a half times greater than the value of the moderately hydraulic lime and five and a half times greater than the feebly hydraulic lime (average linear strain was: 3.95 x 10^{-4} in./in., 1.20 x 10^{-4} in./in., and 6.02 x 10^{-5} in./in. respectively). In this case, the addition of Superior Additive 200 increased linear strain of all mortars: 4% for the cement/lime putty mortars (4.11 x 10^{-4} in./in.), 42% for the feebly hydraulic lime (8.57 x 10^{-5}), and 8% for the moderately hydraulic lime (1.30 x 10^{-4}). These results are not consistent with the water absorption data (see section 5.5). It was expected that the cement/lime mortar would exhibit lower linear strain due to its lower water absorption capacity. In addition, the acrylic emulsion should have decreased the water absorption capacity of all mortars, thus their linear strain. The sandstone exhibited a linear strain (2.77 x 10^{-4} in./in.) higher than all hydraulic lime mortars, but lower than both cement/lime putty mortars. Based on the hydric expansion data, the cement/lime putty mortar without acrylic emulsion is the best compromise for composite repair of the sandstone tested because it is most compatible with the stone, though its linear strain is 30% higher.

5.3 WATER VAPOR TRANSMISSION

Water is present in a masonry system in the liquid and vapor state. Water vapor which can become liquid water through condensation or hygroscopicity can enable the transport of water in a masonry system. In conditions of optimal ground water pressure, wind pressure, temperature, and relative humidity, proper water vapor permeability in the composite repair mortar will draw moisture away from the surrounding stone and transport it to the exterior surface decreasing the accelerated decay caused by freeze/thaw cycles and salt crystallization within the stone.

The results of the water vapor transmission test show that the permeability for the cement/lime putty mortar are consistent with published research.[53] Upon hardening, Portland cement forms a crystalline network of calcium silicate hydrate which replaces the voids left by the free water in the mix and thus results in very small pores, decreasing permeability. The average permeability of the cement/lime putty mortar samples in this research was 53% less than the permeability of the feebly hydraulic lime mortars and 38% less than that of the moderately hydraulic lime mortars (average permeabilities were: 7.26×10^{-8} perm-cm, 1.56×10^{-7} perm-cm, and 1.17×10^{-7} perm-cm respectively).

[53] Judith Jacob and Norman R. Weiss, “Laboratory Measurements of Water Vapor Transmission Rates of Masonry Mortars and Paints,” *APT Bulletin* 21 (no. 3/4, 1989): 66.

According to published research, Superior Additive 200 would decrease water vapor transmission, permeance, and thus permeability.[54] This occurred for the cement/lime putty mortars with a 21% decrease in permeability (5.72×10^{-8} perm-cm) and for the feebly hydraulic lime mortars with a 30% decrease (1.09×10^{-8} perm-cm). However, the moderately hydraulic lime mortars exhibited a 28% increase in permeability (1.50×10^{-7} perm-cm). In this case, a possible explanation is that the air entraining property of the acrylic polymer emulsion discussed in published research could have created a more porous material with greater water vapor transmission, permeance, and permeability.[55]

The mortar with the lowest permeability, cement/lime putty with Superior Additive 200, still has a value approximately four times greater than the permeability of the Connecticut brownstone (1.18×10^{-8} perm-cm). Therefore, none of the composite repair mortars tested runs the risk of trapping water vapor at the mortar/stone interface and thereby accelerating decay. If different permeabilities exist at the interface, internal stresses will result due to salt crystallization growth or freeze/thaw cycling fed by the water vapor. This is a common cause of structural failure in porous building materials.[56] It must be noted that the test was carried out on un-weathered stone. Weathered stone could have significantly different (higher) water vapor transmission, permeance, and permeability.

---

[54] J.A. Lavell, "Acrylic Modified Portland Cement," (Paper Presented at the American Concrete Institute Fall Convention), 1983; Ohama and Ramachandran, 610.

[55] Ohama and Ramachandran, 584-85; V. Ramakrishnan, *Latex-Modified Concretes and Mortars.* National Cooperative Highway Research Program Synthesis of Highway Practice 179 (Washington, DC: Transportation Research Board, National Research Council, 1992), 28.

[56] Giorgio Torraca, *Porous Building Materials: Materials Science for Architectural Conservation*. (Rome: ICCROM, 1982):109.

5.4 WATER ABSORPTION AND EVAPORATION

The other state in which moisture is present in a masonry system is as a liquid. The liquid moves through the system via two mechanisms: capillarity and infiltration. The water absorption test is useful for providing information on the capacity of water absorption and, more critically, the apparent porosity of a composite repair mortar. One study suggests that a mortar "should not be water repellent, but should absorb its generous share of the water circulating in the masonry pores."[57] With respect to composite repair mortars, this is to impede water mobility into the stone which accelerates decay.

The average water absorption of the cement/lime samples was 20% less than that of the moderately hydraulic lime but slightly higher than that of the feebly hydraulic lime (average water absorbed was: 10.82%, 13.60%, and 10.68% respectively). All of the mortars reached their saturation level approximately ten minutes after immersion commenced. Similarly, the average apparent porosity of the cement/lime putty samples was 15% less than the moderately hydraulic lime and slightly less than the feebly hydraulic lime (average apparent porosities were: 20.32%, 24.03%, and 20.79%). It must be noted that the calculated values of absorption capacity and apparent porosity for the cement/lime putty and feebly hydraulic lime samples show an inconsistency. The higher absorption capacity of the cement/lime putty samples with respect to the feebly hydraulic lime samples should have correlated with a higher apparent

[57] S. Peroni et al., "Lime Based Mortars for the Repair of Ancient Masonry and Possible Substitutes," in *Mortars, Cements and Grouts used in the Conservation of Historic Buildings*. (Rome: ICCROM, 1982): 71.

porosity, but the calculated value of apparent porosity for the cement/lime putty was slightly less than that of the feebly hydraulic lime. In this case, the error is considered negligible because the calculated values of water absorption capacity and apparent porosity for the two mortars are virtually identical. However, the results for the feebly hydraulic lime mortar present a more significant inconsistency. With a permeability approximately two times that of the cement/lime putty mortar, the feebly hydraulic lime mortar was expected to have a much greater water absorption capacity than that of the cement/lime putty blend.

As with permeability, it was expected that the addition of Superior Additive 200 would decrease water absorption capacity, and thus apparent porosity. The average water absorption capacity of the cement/lime putty mortars decreased to from 10.92% to 9.17%, but that of the feebly and moderately hydraulic lime mortars increased from 10.68% to 12.66% and from 13.60% to 13.83% respectively. Similarly, the average apparent porosity of the cement/lime putty mortars decreased from 20.32% to 17.89%, and that of the feebly hydraulic and moderately hydraulic lime mortars increased from 20.79% to 23.09% and from 24.03% to 24.43% respectively.

The ability for a material to evaporate the moisture contained within it also plays a critical role in the effect of water mobility and salt crystallization. The evaporation rate of a composite repair mortar should be higher than the rate of evaporation of the surrounding stone to allow for a more efficient transport of moisture out of the masonry system.[58] The critical moisture content determined from the drying test defines the transition from the capillarity of water to the diffusion of water vapor in a material, eventually resulting in evaporation depending upon porosity, pore size, and environmental conditions. The rate of diffusion, a less efficient mechanism for drying, varied between the cement/lime putty and both lime mortars (diffusion being represented by the figures below the determined critical moisture content). The cement/lime putty mortar reached an asymptotical state after the eighth day of drying and both the feebly and moderately hydraulic lime mortars after the seventh day. Superior Additive 200 had no effect on the drying rates of any of the mortar samples. The longer rate of evaporation by vapor diffusion for the cement/lime putty mortar would suggest a tendency for the mortar to retain moisture in the masonry system longer encouraging decay.

The Connecticut brownstone samples tested had an average water absorption capacity of 2.76% and reached their saturation level approximately ten minutes after immersion. The average apparent porosity of the sandstone samples was 6.79%. These values are significantly lower than those for any of the mortars with or without acrylic emulsion; however, mortars with a higher value for porosity are generally desirable. Additionally, the sandstone reached an asymptotical state after the fifth day of drying, two days shorter than for any of the mortars. Based on the water absorption and evaporation results, the cement/lime putty mortar with acrylic emulsion or the feebly hydraulic lime mortar

[58] Thomas, 89.

without acrylic emulsion would be best suited for composite repair of the sandstone tested.

5.5 Flexural Strength and Modulus of Elasticity

Flexural strength is an indication of a composite repair mortar's resistance to cracking under bending stress resulting from differential movement between the mortar and surrounding stone induced by thermal cycles, water absorption and evaporation, or fluctuations in humidity. Related to flexural strength, elasticity is an indication of the mortar's stiffness, or resistance to bending. It is desirable to have a repair mortar with a lower modulus of elasticity than that of the stone so that stress induced by expansion and contraction will be absorbed by the mortar and not cause the repair to crack or pop out.[59] The ideal composite repair has high flexural strength and a low modulus of elasticity.

The results of the flexural strength test are not entirely as expected. The cement/lime putty mortars tested had a flexural strength approximately two times greater than the flexural strength of the feebly hydraulic lime mortars and three times greater than that of the moderately hydraulic lime (average flexural strengths were: 198.67 psi, 61.96 psi, and 51.25 psi respectively). However, the flexural strength of the moderately hydraulic lime mortars, which should have tested higher than the feebly hydraulic lime mortars, was 17% less than the flexural strength of the feebly hydraulic lime. It must be noted that the flexural

[59] This applies to shallow repairs less than two inches. For deeper repairs, where the mortar is expected to bear more of the weight of the masonry above, the repair should have a modulus of elasticity – measured in compression rather than bending – compatible with that of the stone.

strength test was conducted after 90 days of curing, which is considerably shorter than the time required for lime-based mortars to fully carbonate and reach their ultimate strength. This is not a critical issue for the cement/lime putty mortars as the cement dominates early strength.

Published research indicates that the addition of Superior Additive 200 would increase the flexural strength of the mortars.[60] This held true for the cement/lime putty mortars with an increase in flexural strength of 39% (276.98 psi), but the flexural strength of the feebly hydraulic lime was decreased by 19% (50.20 psi). The flexural strength of the moderately hydraulic lime exhibited almost no change with a slight decrease of 2% (50.06 psi).

The Connecticut brownstone samples were the strongest tested with a flexural strength of 518.68 psi. This is 87% higher than the value of the strongest mortar, which was the cement/lime putty with acrylic emulsion. As desired, all of the mortars tested would fail before induced stress could damage the surrounding stone.

The results for modulus of elasticity correlate with the values for flexural strength. The cement/lime putty mortars exhibited a modulus of elasticity approximately two times greater than that of the feebly hydraulic lime mortars and two and a half times greater than the moderately hydraulic lime (average moduli of elasticity were: 7.09×10^4 psi, 2.38×10^4 psi, and 1.95×10^4 psi respectively). Similar to flexural strength, the modulus of elasticity of the

[60] Lavell; Ohama and Ramachandran, 587.

moderately hydraulic lime mortars was 18% lower than the value for the feebly hydraulic lime.

Superior Additive 200 had a more consistent effect on the results for modulus of elasticity. For all the mortars tested, the addition of the acrylic emulsion increased their modulus of elasticity: 72% for cement/lime (1.22×10^5 psi), 11% for feebly hydraulic lime (2.64×10^4 psi), and 2% for moderately hydraulic lime (1.98×10^4 psi). These results contradict published research which indicates that acrylic emulsions should decrease modulus of elasticity.[61]

The sandstone tested had the highest modulus of elasticity with a value of 1.29×10^5 psi. However, this is only 6% higher than the modulus of elasticity of the cement/lime putty mortars with acrylic emulsion. In terms of strength and elasticity, the cement/lime putty mortar without acrylic emulsion would provide the best compromise for use as a composite repair material for this sandstone because it exhibits a flexural strength significantly higher than the hydraulic limes and a modulus of elasticity significantly lower than the cement/lime putty mortar with acrylic emulsion.

Overall, the flexural strengths and moduli of elasticity for the mortars were quite low. One reason may be that the bending test is more accurate for materials that are homogeneous and isotropic. In this research, the mortars are anisotropic due to incomplete carbonation of the lime and may therefore reduce the loads recorded in the test. Additionally, the mortars may not be homogeneous due to small voids introduced during molding. The results for the

---

[61] Ohama and Ramachandran, 598.

stone could be misleading because the samples were relatively slender. With such large-grained stone, larger samples could yield much greater flexural strength and modulus of elasticity.

One problem identified is that the surface of many of the samples was not in complete contact with the loading nose at the start of the test. As a result, the initial portion of the load-deflection curve was altered. This is problematic because the slope of the curve is needed to calculate modulus of elasticity.

5.6 Salt Crystallization Resistance

The most deleterious effects of water in a masonry system can be connected to its transport of soluble salts. The salt resistance test implemented in this research subjected the mortar samples to a 10% solution of sodium sulfate to simulate accelerated weathering. This test has been criticized for inapplicability due to the rapid deterioration exhibited by mortars containing calcium carbonate, though no other standardized test has replaced it.[62]

The cement/lime putty mortars in this research, as expected, exhibited little to no deterioration after the salt crystallization test. Similarly, the moderately hydraulic lime mortars exhibited only minor deterioration. However, the feebly hydraulic lime mortar experienced cracking and severe deterioration of all surfaces. One explanation is that the crystallization and dissolution of salts takes place primarily in medium to large pores which is accommodated for in lime-

[62] S. Peroni et al., 71.

based mortars.[63] In addition, lime mortars are generally known to have less cohesive strength than Portland cement mortars.[64]

Superior Additive 200 negligibly affected the resistance of the cement/lime putty and moderately hydraulic lime mortars. However, the average weight loss of the feebly hydraulic lime mortars at the end of the test decreased significantly from 21.4% to 8.4%. This is probably due to increased grain to grain cohesive strength with the addition of the acrylic emulsion.

The high resistance of the cement/lime putty mortars would suggest that they are acceptable for use as a composite repair for sandstone. It has been published, however, that Portland cement forms soluble salts of sodium and potassium upon setting which are leached long thereafter into the masonry system.[65] Therefore, either of the moderately hydraulic lime mortars, with or without acrylic emulsion, would be a better choice.

5.7 Frost Resistance

The frost resistance test implemented in this research subjected the mortar samples to 15 freeze/thaw cycles to simulate natural climatic moisture and temperature variations. This test is very aggressive in that the samples are fully saturated before freezing, a condition that rarely occurs in practice. However, the 15 cycle duration is not sufficient to test the most durable mortars.

---

[63] Thomas, 91.
[64] Hill and David, 175.
[65] Peron et al., 71.

The results of the freeze/thaw test were as expected for the mortars without Superior Additive 200. The cement/lime putty mortars exhibited little to no deterioration at the end of test. Both the feebly and moderately hydraulic lime mortars exhibited significant deterioration with a final bulk volume of 87.8% and 55.8% respectively. Additionally, one of the moderately hydraulic lime samples broke during the test. As with the salt resistance test, this is probably due the lower cohesive strength of lime mortars. In the case of the moderately hydraulic lime, this can be explained by its higher water absorption capacity.

The addition of Superior Additive 200 had an insignificant effect on the cement/lime putty mortars. However, the acrylic emulsion reduced the overall durability of the hydraulic lime mortars. The final bulk density of the feebly hydraulic lime mortars decreased drastically to 33.1%. Though the final bulk density of the moderately hydraulic lime mortars was unchanged, all three samples broke horizontally into two pieces. Nothing in the literature suggests why acrylic emulsion would decrease the frost resistance of mortar. One explanation is that the acrylic emulsion increased the water absorption capacity of the lime mortars (see section 5.5). Possibly the constant exposure to water (in this test the samples are never allowed to dry) caused the coalesced polymer film to swell which induced more internal stress in the lime mortar samples in addition to the expansion from freezing.[66]

[66] Dossett, 78.

5.8 SUMMARY

There is no perfect composite repair mortar for sandstone. The critical properties of the repair depend on the nature and condition of the particular stone to be repaired, the environment, and the application. The following summary is not intended to identify which mortar tested will yield the best composite repair. Instead, it will emphasize the effect that the different binders tested have on the properties of a repair mortar. Depending on the type of stone, its condition, location, and environment, the components of a composite repairs mortar can be manipulated to provide optimal performance. The results of all the tests conducted in this research are summarized in Tables 5.2 and 5.3.

Table 5.2: Summary of Test Results

Sample	Total liquid (ml)	Time to reach full set (hours)	Drying shrinkage (%)	Coefficient of thermal expansion (in/in·°F)	Linear strain due to water absorption (in/in)	Average water vapor transmission ($g/h \cdot m^2$)	Average permeability (perm-cm)
A	190.00	1.33	0.059	3.31E-06	3.96E-04	0.45	7.26E-08
B	180.00	1.00	0.053	3.84E-06	4.11E-04	0.36	5.72E-08
C	460.00	5.92	0.031	4.21E-06	6.02E-05	0.97	1.56E-07
D	410.00	4.58	0.030	4.23E-06	8.57E-05	0.68	1.09E-07
E	460.00	5.50	0.059	4.72E-06	1.20E-04	0.73	1.17E-07
F	390.00	3.67	0.034	4.24E-06	1.30E-04	0.94	1.50E-07
S	---	---	---	6.27E-06	2.77E-04	0.07	1.18E-08

Table 5.3: Summary of Test Results (continued)

Sample	Imbibition capacity (% dry weight)	Average apparent porosity (%)	Evaporation time (days)	Flexural strength (psi)	Modulus of elasticity (psi)	Salt crystallization weight change (%)	Frost resistance (% bulk volume retained)
A	10.82	20.32	8	198.67	7.09E+04	2.78	100.72
B	9.17	17.89	8	276.98	1.22E+05	2.77	100.23
C	10.68	20.79	7	61.96	2.38E+04	-21.44	87.78
D	12.66	23.09	7	50.20	2.64E+04	-8.44	33.06
E	13.60	24.03	7	51.25	1.95E+04	1.48	55.84
F	13.83	24.43	7	50.06	1.98E+04	2.10	101.00
S	2.76	6.79	5	518.68	1.29E+05	---	---

Key to Samples	
Group A	cement/lime putty mortars
Group B	cement/lime putty mortars with acrylic
Group C	feebly hydraulic lime mortars
Group D	feebly hydraulic lime mortars with acrylic
Group E	moderately hydraulic lime mortars
Group F	moderately hydraulic lime mortars with acrylic
Group S	Connecticut brownstone

When the test results for the cement/lime mortar were compared with the combined results for the feebly and moderately hydraulic lime, general trends became apparent. However, a few anomalies arose when the overall effects of Superior Additive 200 were studied. One explanation for these inconsistencies is that acrylic admixtures are formulated specifically for use with Portland cement mortars. Further research needs to be conducted in order to gain a better understanding of the reaction of acrylic admixtures with pure lime mortars.

The setting time for the cement/lime mortar was shorter than for the hydraulic lime mortars, but the lime mortars exhibited less drying shrinkage. As expected, both setting time and drying shrinkage were decreased for all mortars with the addition of the acrylic emulsion. The cement/lime putty mortar demonstrated less thermal expansion but more hydric expansion than the hydraulic lime mortars. Superior Additive 200 increased thermal and hydric expansion in all mortars except for the moderately hydraulic lime. The permeability and porosity of the cement/lime mortar was lower than the hydraulic lime mortars. Permeability and porosity of the cement/lime putty mortar were decreased by the acrylic emulsion as expected. However, these values for the lime mortars were increased by the acrylic emulsion except for the permeability of the feebly hydraulic lime. The cement/lime putty mortar produced significantly higher values for both flexural strength and modulus of elasticity than the lime mortars. The acrylic emulsion increased these values for all mortars except the flexural strength of the hydraulic lime. The cement/lime putty mortar was more resistance to salt crystallization and freeze/thaw cycling. The only notable effect of Superior Additive 200 is that is significantly decreased the durability of the feebly hydraulic lime mortar, which is contrary to the expected result.

A comparison of the results from this testing program with those from the past research conducted at the University of Pennsylvania reveals many similarities. The cement/lime mortars set faster and were less permeable, stronger, and more durable than the lime-based mortars. The acrylic emulsion, Acryl 60 in this case, also produced inconsistent effects. Results from the past research are summarized in Tables 5.4 and 5.5.

Table 5.4: Summary of Test Results from Past Research

Sample	Flow (%)	Total liquid (ml)	Time to reach full set (h:m:s)	Average water vapor transmission ($g/m \cdot m^2$)	Average permeance ($g/Pa \cdot s \cdot m^2$)	Absorption capacity (% dry weight)
A	27.00	100	63:30:00	9.22	2.09E-06	9.76
B	30.57	85	52:00:00	9.37	2.12E-06	15.23
C	28.00	169	7:00:00	8.14	1.85E-06	9.45
D	31.23	143	6:00:00	7.11	1.61E-06	7.86
E	33.02	130	2:30:00	4.85	1.10E-06	8.84
F	31.25	108	2:45:00	5.88	1.33E-06	9.77
G	31.25	113	3:15:00	5.75	1.30E-06	10.54
H	29.31	98	3:00:00	6.78	1.54E-06	10.12
I	19.30	138	2:00:00	4.89	1.11E-06	9.93
S	---	---	---	1.17	2.64E-07	---

Table 5.5: Summary of Test Result from Past Research (continued)

Sample	Flexural strength (psi)	Modulus of elasticity (psi)	Bond strength - shear stress at failure (psi)	Frost resistance (% bulk volume retained)	Salt crystallization rating (comparative visual analysis)	Abrasion resistance - indirect weight of loss (g)
A	130.30	3.42E+03	19.27	0	4	0.45
B	100.72	4.82E+03	10.58	0	5	0.26
C	119.98	5.27E+03	19.44	97.8	7	0.50
D	256.31	1.70E+04	31.83	94.5	9	0.16
E	451.17	2.40E+04	76.13	99.9	10	0.18
F	457.80	2.01E+04	49.29	99.8	10	0.15
G	306.59	2.00E+04	60.77	98.2	7	0.20
H	398.44	2.29E+04	26.45	99.5	9	0.14
I	573.18	3.87E+04	36.77	99.3	10	0.25
S	1827.60	4.12E+04	---	---	---	0.07

Key to Samples	
Group A	lime putty mortars
Group B	lime putty mortars with acrylic
Group C	hydraulic lime mortars
Group D	hydraulic lime mortars with acrylic
Group E	1:1 cement/lime putty mortars
Group F	1:1 cement/lime putty mortars with acrylic
Group G	1:2 cement/lime putty mortars
Group H	1:2 cement/lime putty mortar with acrylic
Group I	Jahn M70 #2

5.9 Future Testing

The next phase of research relating to the composite repair mortars for sandstone should investigate the mortar formulations in this research after one year of curing in the same conditions. The same tests should be run, but the inclusion of additional materials, such as St. Astier eminently hydraulic lime and inorganic pigments, should be considered. Lastly, microstructure examination with x-ray diffraction analysis of the carbonation of the lime-based mortars would further the discussion on permeability, porosity, and strength.

BIBLIOGRAPHY

ASM Handbook, 10th ed., vol. 1. Materials Park, OH: ASM International, 1990.

Ashurst, John. "Cleaning and Surface Repair." *APT Bulletin* 17 (no. 2, 1985): 39-42.

Ashurst, John. *Mortars, Plasters and Renders in Conservation*. Leominster, England: Orphans Press Ltd., 2002.

Ashurst, John. *Stone in Building: Its Use and Potential Today*. London: Architectural Press, 1977.

Ashurst, John and Nicola Ashurst. "Mortars, Plasters and Renders." In *Practical Building Conservation,* vol. *3*. Hants, England: Gower Technical Press, 1988.

Ashurst, John and Francis G. Dimes, eds. *Conservation of Building & Decorative Stone*. Oxford: Butterworth Heinemann, 1998.

Ashurst, Nicola. *Cleaning Historic Buildings*. London: Donhead, 1994.

Banfill, P.F.G. and A.M. Forster. "A Relationship Between Hydraulicity and Permeability of Hydraulic Lime." In *International RILEM Workshop on Historic Mortars: Characteristics and Tests Held in Paisley, Scotland 12-14 May 1999,* 173-183. Paisley, Scotland: RILEM Publications S.A.R.L., 1999.

Baronio, G., L. Binda, and A. Saisi. "Mechanical and Physical Behaviour of Lime Mortars Reproduced After the Characterization of Historic Mortar." In *International RILEM Workshop on Historic Mortars: Characteristics and Tests Held in Paisley, Scotland 12-14 May 1999,* 307-325. Paisley, Scotland: RILEM Publications S.A.R.L., 1999.

Beckmann, Poul. *Structural Aspects of Building Conservation.* Boston: Elsevier Butterworth-Heineman, 2004.

Biscontin, Guido and Laura Graziano, eds. *Conservation of Architectural Surfaces: Stones and Wall Covering*. Venice: il Cardo, 1993.

Blades, Keith, Gail Sussman, and Martin Weaver. *Masonry Conservation and Cleaning Handbook*. Ottawa, Ontario, 1985.

Blatt, H. *Sedimentary Petrology,* 2d ed. New York: W.H. Freeman & Co., 1992.

Bowles, Oliver. *The Stone Industries*. New York and London: McGraw Hill, 1934.

Boyer, David W. “Masonry Cleaning – The State of the Art.” In *Cleaning Stone and Masonry: A Symposium Sponsored by ASTM Committee E-6 on Performance of Building Constructions Held in Louisville, KY 18 April 1983, ASTM STP 935,* edited by James R. Clifton, 25-51. Philadelphia: American Society for Testing and Materials, 1986.

Brownstone: An Owner’s Care and Repair Guide. Society for the Preservation of New England Antiquities.

Boynton, Robert S. *Chemistry and Technology of Lime and Limestone*. New York: John Wiley and Sons, 1980.

Cappeto, Jennifer E. “A Performance Analysis of Repair Mortars for the Ayyubid Wall of Cairo.” Master’s Thesis, University of Pennsylvania, 2003.

Caroe, A.D.R. and M.B. Caroe. *Stonework: Maintenance and Surface Repair,* 2d ed. London: Church House Publishing, 2001.

Carrington, David and Peter Swallow. “Limes and Lime Mortars – Part 2.” *Journal of Architectural Conservation* 2 (no. 1, March 1996): 7-22.

Charola, A. Elena. “Laboratory Tests and Evaluation of Proposed Masonry Treatments.” *APT Bulletin* 26 (no. 4, 1995): 35-39.

Charola, A. Elena. “Salts in the Deterioration of Porous Materials: An Overview.” *Journal of the American Institute for Conservation*, 39. (2000):327-343.

Charola, A. Elena and Fernando M.A. Henriques. “Hydraulicity in Lime Mortars Revisited.” In *International RILEM Workshop on Historic Mortars: Characteristics and Tests Held in Paisley, Scotland 12-14 May 1999,* 95-104. Paisley, Scotland: RILEM Publications S.A.R.L., 1999.

Charola, A. Elena, E. De Witte and M. Laurenzi Taabasso. “Establishing International Standards for the Quality Control of Conservation Materials and for Qualifying Practitioners Applying Them.” In *Report of the Dahlem Workshop on Saving Our Architectural Heritage: The Conservation of Historic Stone Structures Held in Berlin 3-8 March 1996*, edited by N.S. Baer and R. Snethlage, 245-54. Chichester, New York, Weinheim, Brisbane, Singapore, and Toronto: John Wiley & Sons, 1997.

Charola, A. Elena and F.M.A. Henriques. “Lime Mortars: Some Considerations on Testing Standardization.” In *Use of and Need for Preservation Standards in Architectural Conservation, ASTM STP 1355,* edited by L.B. Sickels-Taves, 142-151. West Conshohocken, PA: American Society for Testing and Materials, 1999.

Charola, A. Elena and Johannes Weber. "The Hydration-Dehydration Mechanism of Sodium Sulphate." In *Proceedings of the 8th Congress on Deterioration and Conservation of Stone Held in Berlin, 30 September – 4 October, 1996*, edited by Josef Riederer, 581-590. Berlin: Moeller Druck und Verlag, 1996.

Clifton, J.R., B.E. Foster, E. Trattner, and R.A. Clevenger. "Dimensional Stability of Masonry Walls." In *Masonry, Past and Present, ASTM STP 589,* 42-75. Philadelphia: American Society of Testing and Materials, 1975.

Cliver, Blaine E. "Tests for the Analysis of Mortar Samples." *APT Bulletin* 6 (no. 1, 1974): 68-73.

Cowan, Henry J. and Peter R. Smith. "Gypsum, Lime and Cement." In *The Science and Technology of Building Materials*. New York: Van Nostrand Reinhold, 1988.

Cowper, A.D. *Lime and Lime Mortars*. Shaftesbury, England: Donhead Publishing Ltd., 1998.

Dossett, James W. "Composite Repair of Sandstone." Master's Thesis, University of Pennsylvania, 1998.

Edison, Michael P. "Color and Long-Term Color Retention." *APT Bulletin* 33 (no. 2/3, 2002): 23-32.

Edison, Michael P. "Custom Latex-Modified Cement Repair Mortars for Masonry." *Concrete Repair Bulletin* (July-August 1991): 7-9, 22.

Ellison, Peter T. "Hydraulic Lime Mortars." Master's Thesis, University of Pennsylvania, 1998.

El Rey Stucco Company, Inc. Superior Additive 200. Product Literature, n.d.

English Heritage. *Hybrid Mortar Mixes containing a blend of both non-hydraulic lime and hydraulic lime binders*. Technical Policy Statement. London: English Heritage, 1997.

Emley, Warren E. *Technologic Papers of the Bureau of Standards, No. 169: Measurement of Plasticity of Mortars and Plasters*. Washington, D.C.: Government Printing Office, 1920.

Erdly, Jeffrey L. "Application Procedures for Masonry Treatments." *APT Bulletin* 26 (no. 4, 1995): 46-49.

Feilden, Bernard M. *Conservation of Historic Buildings*. Oxford: Architectural Press, 2000.

Foulks, William G., ed. *Historic Building Facades: The Manual for Maintenance and Rehabilitation*. New York: Wiley, 1997.

Gannet, H. *Report on the Building Stones of the United States and Statistics of the Quarry Industry for 1880*. Washington, DC: Government Printing Office, 1883.

Gauri, K.L., G.C. Holdren, and W.C. Vaughan. "Cleaning Efflorescences from Masonry." In *Cleaning Stone and Masonry, ASTM STP 935,* edited by J.R. Clifton. Philadelphia: American Society of Testing and Materials, 1986.

GenLime, Inc. Niagara® Mature Lime Putty. Product Literature, n.d.

Gillmore, Q.A. *Practical Treatise on Limes, Hydraulic Cements and Mortars*. New York: D. Van Nostrand, 1874.

Grimm, C.T. "Water Permeance of Masonry Walls: A Review of the Literature." In *Masonry: Materials, Properties, Performance, ASTM STP 778,* edited by J.G. Borcheldt, 178-199. Philadelphia: American Society for Testing and Materials, 1982.

Grimmer, A.E. *A Glossary of Historic Masonry Deterioration Problems and Preservation Treatments*. Washington, D.C.: NPS Preservation Assistance Division, 1984.

Griswold, John and Sari Uricheck. "Loss Compensation Methods for Stone." *Journal of the American Institute for Conservation* 37 (1998): 89-110.

Handbook of Chemistry and Physics, 74th ed. Boca Raton, FL: CRC Press, 1994-95.

Hansen, Eric F., Alberto Tagle, Evin Erder, Susan Baron, Samuel Connell, Carlos Rodriguez-Navarro and Koenraad van Balen. "Effects of Ageing on Lime Putty." In *International RILEM Workshop on Historic Mortars: Characteristics and Tests Held in Paisley, Scotland 12-14 May 1999,* 197-206. Paisley, Scotland: RILEM Publications S.A.R.L., 1999.

Harris, Harry A. "A Method to Determine Efflorescence and Water Permeance of Masonry Mortars." In *Masonry: Research, Application, and Problems. A symposium sponsored by ASTM committees C-7 on Lime, C-12 on Mortars for Unit Masonry, and C-15 on Manufactured Masonry Units Held in Bar Harbor, FL 6 December, 1983*, edited by J.C Grogan, and J.T. Conway, 88-100. Philadelphia: 1985.

Henriques, F.M.A. “Testing Methods for the Evaluation of New Mortars for Old Buildings.” *Science and Technology for Cultural Heritage* 5, (no. 1, 1996): 57-61.

Henriques, Fernando M.A. and A. Elena Charola. “Comparative Study of Standard Test Procedures for Mortars.” In *Proceedings of the 8th International Congress on Deterioration and Conservation of Stone*, edited by J. Riederer, 1521-1528. Berlin: Moeller Druck und Verlag, 1996.

Hill, P.R. and J.C.E. David. *Practical Stone Masonry*. London: Donhead, 1995.

Hughes, D.C. and D.B. Sugden. “A Comparative Study of Hydraulic Lime-Based Mortars.” In *International RILEM Workshop on Historic Mortars: Characterization and Tests Held in Paisley, Scotland 12-14 May 1999,* 351-359. Paisley, Scotland: RILEM Publications S.A.R.L.., 1999.

Hughes, John J. and Jan Válek. *Mortars in Historic Buildings: A Review of the Conservation, Technical, and Scientific Literature*. Edinburgh: Historic Scotland, 2003.

Iveson, A.S. *Masonry Conservation and Restoration*. London: Attic Books, 1987.

Jacob, Judith and Norman R. Weiss. “Laboratory Measurement of Water Vapor Transmission Rates of Masonry Materials and Paints.” *APT Bulletin* 21 (no. 3/4): 62-70.

Jornet, Albert. “Slaked Lime Mortar: Comparison Between Two Samples Supposed to be Alike.” In *Proceedings of the 9th International Congress on the Deterioration and Conservation of Stone Held in Venice 19-24 June 2000*, edited by Vasco Fassina, 343-350. Amsterdam: Elsevier: 2000.

Julien, Alexis A. “The Decay of the Building Stones of New York City.” *Transactions of the New York Academy of Sciences* (January 29, 1883): 67-138.

Karaveziroglou, M.; Papayianni, I. “Compressive Strength of Masonry with Thick Mortar Joints.” In *Conservation of Stone and Other Materials: Proceedings of the International RILEM/UNESCO Congress Held in Paris 29 June-July 1, 1993*. edited by M.J. Thiel, 212-219. London: E. & F.N. Spon Ltd., 1993.

Koestler, R.J., T. Warscheid, and F. Neito. “Bioterioration: Risk Factors and Their Management.” In *Report of the Dahlem Workshop on Saving Our Architectural Heritage: The Conservation of Historic Stone Structures Held in Berlin 3-8 March 1996*, edited by N.S. Baer and R. Snethlage, 25-36. Chichester, New York, Weinheim, Brisbane, Singapore, and Toronto: John Wiley & Sons, 1997.

Korpan, Dean. “Composite Stone Repairs at Drayton Hall.” *APT Bulletin* 14 (no. 3, 1982): 37-41.

Lavelle, J.A. “Acrylic Modified Portland Cement.” Paper Presented at the American Concrete Institute Fall Convention Held in Baltimore, 1986.

Lea, F. M. *The Chemistry of Cement and Concrete*. New York: Chemical Publishing Company, 1970.

Lehigh Cement Company. Type I Portland Cement. Product Literature, n.d.

Lewin, S.Z. “The Mechanism of Masonry Decay Through Crystallization.” In *Conservation of Historic Stone Buildings,* 120-44. Washington: Committee on Conservation of Historic Stone Buildings and Monuments, National Materials Advisory Board, Commission on Engineering and Technical Systems, National Research Council, 1982.

Lewin, S.Z. “The Current State of the Art on the Use of Synthetic Materials for Stone Conservation – Inorganic and Metal-Organic Compounds.” In *Deterioration and Conservation of Stone: Notes from the International Venetian Course on Stone Restoration,* edited by Lorenzo Lazzarini and Richard Pieper, 290-302. Venice: UNESCO, 1988.

Livesey, Paul. “Succeeding with Hydraulic Lime Mortars.” *Journal of Architectural Conservation* 2 (no. 2, July 2002): 23-37.

London, Mark. *Masonry: How to Care for Old and Historic Brick and Stone*. Washington, DC: The Preservation Press, 1988.

Lynch, Michael F. and William J. Higgins. *The Maintenance and Repair of Architectural Sandstone*. New York: New York Landmarks Conservancy, 1982.

Maurenbrecher, A.H.P., G.T. Suter, K. Trischuk, and L. Fontaine. “Contribution to Pointing Mortar Durability.” In *International RILEM Workshop on Historic Mortars: Characteristics and Tests Held in Paisley, Scotland 12-14 May 1999,* 361-367. Paisley, Scotland: RILEM Publications S.A.R.L., 1999.

Matero, Frank G. and Anne B. Oliver. “A Comparative Study of Alkoxysilanes and Acrylics in Sequence and in Mixture.” *Journal of Architectural Conservation* 3 (no. 1, July 1997): 22-42.

Matero, Frank G. and Jeanne Marie Teutonico. “The Use of Architectural Sandstone in New York City in the 19th Century.” *APT Bulletin* 14 (no. 2, 1982): 11-17.

McKee, Harley J. *Introduction to Early American Masonry*. Washington, DC: National Trust for Historic Preservation, 1973.

Merril, G.P. *Stones for Building and Decoration*. New York: John Wiley & Sons, 1910.

Moropoulou, A. "Reverse Engineering to Discover Traditional Technologies: A Proper Approach for Compatible Restoration Mortars." In *Compatible Materials for the Protection of European Cultural Heritage, PACT 58 Athens,* 81-107. Greece: Technical Chamber of Greece: 2000.

Moropoulou, Antonia, Asterios Bakolas, and Petros Moundoulas. "Criteria and Methodology for Restoration Mortars Compatible to the Historic materials and Structures." In *Proceedings of the 9th International Congress on the Deterioration and Conservation of Stone Held in Venice 19-24 June 2000*, edited by Vasco Fassina, 403-411. Amsterdam: Elsevier: 2000.

Moropoulou, Antonia; Bakolas, Asterios; Michailidis, P.; Chronopoulos, M.; Spanos, Ch. "Traditional Technologies in Crete Providing Mortars with Effective Mechanical Properties." In *Structural studies of historic buildings*. IV, vol. 1, 151-161, 1995.

Moropoulou, A., P. Maravelaki-Kalaitzaki, M. Borboudakis, A. Bakolas, P. Michailidis, and M. Chronopoulos. "Historic Mortars Technologies in Crete and Guidelines for Compatible Restoration Mortars." In *Compatible Materials for the Protection of European Cultural Heritage, PACT 55 Athens,* 55-73. Greece: Technical Chamber of Greece: 1998.

Nordmeyer, Herbert D. "High Pozzolan Mortars and Stuccos" In *Masonry: Opportunities for the 21st Century. Papers of the Tenth Symposium Held in Salt Lake City, Utah 25 June 2002*, edited by Diane Throop and Richard E. Klingner, 36-50. West Conshohocken: ASTM International, 2002.

Ohama, Yoshihiko. "Polymer-Modified Mortars and Concretes." In *Concrete Admixtures Handbook: Properties, Science and Technology,* edited by V.S. Ramachandran, 337-429. Park Ridge, NJ: Noyes Publications, 1984.

Ohama, Yoshihiko and V.S. Ramachandran. "Polymer-Modified Mortars and Concretes." In *Concrete Admixtures Handbook: Properties, Science, and Technology,* 2d ed., edited by V.S. Ramachandran, 558-656. Park Ridge, NJ: Noyes Publications, 1995.

Paloma, Puertas Blanco. “Mortars for Restoration.” In *Proceedings of the 8th International Congress on Deterioration and Conservation of Stone Held in Berlin 30 September-4 October, 1996,* edited by Josef Riederer, 1547-1555. Berlin: Moeller Druck und Verlag, 1996.

Papayianni, I., and K. Theochardiou. “Efflorescence Tendency of Mortars Used in Interventions on Old Masonry.” In *Conservation of Stone and Other Materials: Proceedings of the International RILEM/UNESCO Held in Paris 29 June-1July 1993*, edited by M.J. Thiel, 621-628. London: E & FN Spon, 1993.

Papayianni, Ioanna. “Criteria and Methodology for Manufacturing Compatible Repair Mortars and Bricks.” In *Compatible Materials for the Protection of European Cultural Heritage, PACT 56 Athens*, 179-190. Greece: Technical Chamber of Greece: 1998.

Pasley, C.W. *Observations on Limes*. (Reprint from 1883) Dorset: Donhead Publishing Ltd., 1997.

Park, S.C. *Preservation Briefs 16: The Use of Substitute Materials Used on Historic Building Exteriors.* Washington, DC: National Park Service.

Penelis, G.; Papayanni, J.; Karaveziroglou, M. “Pozzolanic Mortars for Repair of Masonry Structures.” In *Structural Studies of Historical Buildings IV,* edited by C.A. Brebbia, B. Leftheris, vol. 1, 161-169. Southampton, Boston: Computational Mechanics Publications, 1995.

Peroni, S., C. Tersigni, G. Torraca, S. Cerea, M. Forti, F. Guidobaldi, P. Rossa-Doria, A. DeRege, D. Picchi, F.J. Pietrafitta, G. Benedetti. “Lime-Based Mortars for the Repair of Ancient Masonry and Possible Substitutes.” In *Mortars, Cements and Grouts Used in the Conservation of Historic Buildings: Symposium 3-6.11. 1981 Rome*, 63-99. Rome: ICCROM, 1982.

Phillips, Morgan. “A Source of Confusion about Mortar Formulas.” *APT Bulletin* 25 (no. 1, 1994): 50-53.

Phillips, Morgan. “An Actual Mortar Analysis.” *APT Bulletin* 25 (no. 3/4, 1994): 54-55.

Picalli, Joseph and Elizabeth Laycock. “Limestone Mortars as a Problem for Sandstone.” *Journal of Architectural Conservation* 7 (no. 3, November 2001): 24-31.

Puertas, F., M.T. Blanco-Varela, S. Martinez, F. Accion, and G. Alvarez. "Methodology of Analysis of Stones and Mortars in Monuments." In *Proceedings of the 7th International Congress on Deterioration and Conservation of Stone Held in Lisbon, Portugal, 15-18 June 1992*, 763-770. Lausanne: Presses Polytechniques Romandes, 1992.

Price, Clifford A. *Stone Conservation: An Overview of Current Research*. Santa Monica, CA: Getty Conservation Institute, 1996.

Pühringer, Josef and L. Engström. "Unconventional Methods for the Prevention of Salt Damage." In *Proceedings of the 5th International Congress on Deterioration and Conservation of Stone Held in Lausanne, Switzerland,* 241-250. Lausanne: Presses Polytechniques Romandes, 1985.

Pühringer, Josef and Johannes Weber. "A Model for Salt Extraction – Some Principles." In *Preprints of the 9th Triennial Meeting of the ICOM Committee for Conservat*ion, 355-360. Los Angeles: ICOM Committee for Conservation, 1990.

Ramakrishnan, V. *Latex-Modified Concretes and Mortars.* National Cooperative Highway Research Program Synthesis of Highway Practice 179. Washington, DC: Transportation Research Board, National Research Council, 1992.

RILEM. *Recommended Tests to Measure the Deterioration of Stone and to Assess the Effects of Treatment Methods: UNESCO/RILEM International Symposium on the Deterioration and Protection of Stone Monuments Held in Paris 5-9 June 1978.* Paris: UNESCO/RILEM, 1978.

Robertson, Eugene C. "Physical Properties of Building Stone." In *Conservation of Historic Stone Buildings,* 62-86. Washington: Committee on Conservation of Historic Stone Buildings and Monuments, National Materials Advisory Board, Commission on Engineering and Technical Systems, National Research Council, 1982.

Rodrigues, Jose Delgado. "In Search for Tentative Recommendations Regarding Compatible Restoration Mortars." In *Compatible Materials for the Protection of European Cultural Heritage, PACT 56 Athens*, 141-147. Greece: Technical Chamber of Greece: 1998.

Rossi-Doria and P. Roti. "Mortars for Restoration: Basic Requirements and Quality Control." *Materials and Structures* 19 (no. 114, 1986): 445-448.

Sasse, H.R. and R. Snethlage. “Methods for the Evaluation of Stone Conservation Treatments.” In *Report of the Dahlem Workshop on Saving Our Architectural Heritage: The Conservation of Historic Stone Structures Held in Berlin 3-8 March 1996*, edited by N.S. Baer and R. Snethlage, 223-44. Chichester, New York, Weinheim, Brisbane, Singapore, and Toronto: John Wiley & Sons, 1997.

Schaffer, Robert John. *The Weathering of Natural Building Stones*. London: H.M. Stationery Office, 1932.

Schafer, J. and H.K. Hilsdorf. “Ancient and New Lime Mortars – The Correlation between their Composition, Structure and Properties.” In *Conservation of Stone and Other Materials: Proceedings of the International RILEM/UNESCO Held in Paris 29 June-1 July 1993,* edited by M.J. Thiel, 605-613. London: E & FN Spon, 1993.

Scottish Lime Center. *Technical Advice Note 1: Preparation and Use of Lime Mortars,* revised edition. Edinburgh: Historic Scotland, 2003.

Seeley, Nigel J. “Magnesium and Dolomitic Lime Mortars in Building Conservation.” *Journal of Architectural Conservation* 6 (no. 2, July 2000): 21-29.

Selwitz, C. *Research in Conservation: 7, Epoxy Resins in Stone Conservation*. Marina Del Rey: Getty Conservation Institute, 1992.

Sickels-Taves, Lauren B. and Michael S. Sheehan. *Specifying Historic Materials: The Use of Lime, ASTM STP 1432.* West Conshohocken, PA: ASTM, 2002.

Snethlage, R. and E. Wendler. “Moisture Cycles and Sandstone Degradation.” In *Report of the Dahlem Workshop on Saving Our Architectural Heritage: The Conservation of Historic Stone Structures Held in Berlin 3-8 March 1996*, edited by N.S. Baer and R. Snethlage, 7-24. Chichester, New York, Weinheim, Brisbane, Singapore, and Toronto: John Wiley & Sons, 1997.

Standards for Preservation and Rehabilitation, edited by Stephen J. Kelly. West Conshohocken, PA: ASTM, 1996.

St. Astier. NHL 2 and NHL 3.5. Product Literature, n.d.

Stewart, John, Richard Glover, John Houston, Nigel Seeley and Trevor Proudfoot. “Field and Laboratory Assessment of Lime-Based Mortars.” *Journal of Architectural Conservation* 1 (no. 1, March 2001): 7-41.

Suter, Gary T., Margaret L. Thomson, and Lyne Fontaine. "Mortar Study of Mechanical Properties for the Repointing of the Canadian Parliament Buildings." *APT Bulletin* 29 (no.2, 1998): 51-58.

Suter, G.T., J. Vandenberg, and L. Fontaine. "Bond Capacities of Mortars for Historic Stone." *APT Bulletin* 27 (no. 4, 1996): 27-35.

Swallow, Peter and David Carrington. "Limes and Lime Mortars – Part 1." *Journal of Architectural Conservation* 1 (no. 3, November 1995): 7-25.

Taylor, H.F.W. *Cement Chemistry*. London: Academic Press, 1990.

Teutonico, Jeanne Marie, Iain McCaig, Colin Burns, and John Ashurst. "The Smeaton Project: Factors Affecting the Properties of Lime-Based Mortars." *APT Bulletin* 25 (no. 3/4, 1994): 34-49.

Teutonico, Jeanne Marie, Geoff Ashall, Elizabeth Garrod and Tim Yates. "A Comparative Study of Hydraulic Lime-Based Mortars." In *International RILEM Workshop on Historic Mortars: Characteristics and Tests Held in Paisley, Scotland 12-14 May 1999,* 339-349. Paisley, Scotland: RILEM Publications S.A.R.L., 1999.

The Brownstone Guide: Maintenance and Repair for Historic Property Owners. New York Landmarks Conservancy.

The National Lime Association. Online. Internet 15 July 2005. Available: http://www.lime.org.

Thomas, Amanda B. "Study of the Repair Mortars for the Ayyubid City Wall of Cairo." Master's Thesis, University of Pennsylvania, 2004.

Thompson, Margaret L. "Plasticity, Water Retention, Soundness and Sand Carrying Capacity: What a Mortar Needs." In *International RILEM Workshop on Historic Mortars: Characteristics and Tests Held in Paisley, Scotland 12-14 May 1999,* 163-171. Paisley, Scotland: RILEM Publications S.A.R.L., 1999.

Thompson, Margaret and Casper Groot. "RILEM TC Characterization of Old Mortars with Respect to Their Repair." In *The Use of and Need for Preservation Standards in Architectural Conservation Held in Atlanta 18-19 April 1998, ASTM STP 1355.* West Conshohocken, PA: ASTM, 1998.

Tobasso, M. Laurenzi. "Conservation Treatments of Stone." In *Conservation of Historic Stone Buildings,* 271-89. Washington: Committee on Conservation of Historic Stone Buildings and Monuments, National Materials Advisory Board, Commission on Engineering and Technical Systems, National Research Council, 1982.

Torraca, Giorgio. *Porous Building Materials: Materials Science for Architectural Conservation,* 3d ed. Rome: ICCROM, 1988.

Tougelidis, G. and C.P. Providakis. “Effects of Lime Mortars on Masonry Construction.” In *Structural Studies of Historical Buildings IV*, edited by C.A. Brebbia, B. Leftheris, 215-222. Southampton, Boston: Computational Mechanics Publications, 1995.

Turner, Susan D. “Repair of Stone.” *Heritage* 5 (no. 2, 2002): 18-19.

Vadstrup, Soren. *Technical Instructions for Restoration Works*. Raadvad: Nordisk Center til Bevarelse af Håndvaerk, 2000.

Van Balen, K. and D. Van Gemert. “Modeling Lime Mortar Carbonation.” *Materials and Structures* 27 (1994): 393-398.

Valluzzi, M.R., L. Binda, and C. Modena. “Experimental and Analytical Studies for the Choice of Repair Techniques Applied to Historic Buildings.” *Materials and Structures* 35 (no. 249, 2002): 285-292.

Vicat, L.J. *Mortars and cements,* 1837. Reprint, Dorset: Donhead Publishing Ltd., 1997.

Weber, H. and K. Zinsmeister. *Conservation of Natural Stone: Guidelines to Consolidation, Restoration and Preservation*. Ehninger: expert-Verlag, 1991.

Weiss, Norman R. *Conservation Study: Exterior Stonework, Trinity Church, New York, NY*. New York: Columbia University Center for Preservation Research, 1987.

Weiss, Norman R., Jeanne Marie Teutonico, Frank G. Matero, and R. Pepi. *Sandstone Restoration Study*. New York: New York Landmarks Conservancy, 1982.

Wilson, F. *Building Materials Evaluation Handbook*. New York: Van Nostrand Reinhold, 1984.

Winkler, Erhard M. *Stone in Architecture: Properties, Durability,* 3d ed. Berlin, Heidelberg, New York: Springer-Verlag, 1994.

REFERENCED STANDARDS

American Society for the Testing of Materials Standards. "C5-79(1997): Standard Specification for Quicklime for Structural Purposes." *Annual Book of ASTM Standards*. West Conshohocken, PA: American Society for the Testing of Materials, 2001.

American Society for the Testing of Materials Standards. "C109/C109M-99: Standard Test Method for Compressive Strength of Hydraulic Cement Mortars." *Annual Book of ASTM Standards*. West Conshohocken, PA: American Society for the Testing of Materials, 2001.

American Society for the Testing of Materials Standards. "C136-01: Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates." *Annual Book of ASTM Standards*. West Conshohocken, PA: American Society for the Testing of Materials, 2001.

American Society for the Testing of Materials Standards. "C141-97: Standard Specification for Hydraulic Hydrated Lime for Structural Purposes." *Annual Book of ASTM Standards*. West Conshohocken, PA: American Society for the Testing of Materials, 2001.

American Society for the Testing of Materials Standards. "C144-99: Standard Specification for Aggregate for Masonry Mortar." *Annual Book of ASTM Standards*. West Conshohocken, PA: American Society for the Testing of Materials, 2001.

American Society for the Testing of Materials Standards. "C150-00: Standard Specification for Portland Cement." *Annual Book of ASTM Standards*. West Conshohocken, PA: American Society for the Testing of Materials, 2001.

American Society for the Testing of Materials Standards. "C157/C157M-99: Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete." *Annual Book of ASTM Standards*. West Conshohocken, PA: American Society for the Testing of Materials, 2001.

American Society for the Testing of Materials Standards. "C191-99: Standard Test Method for Time of Setting of Hydraulic Cement by Vicat Needle." *Annual Book of ASTM Standards*. West Conshohocken, PA: American Society for the Testing of Materials, 2001.

American Society for the Testing of Materials Standards. "C192/C192M-00: Practice for Making and Curing Concrete Test Specimens in the Laboratory." *Annual Book of ASTM Standards*. West Conshohocken, PA: American Society for the Testing of Materials, 2001.

American Society for the Testing of Materials Standards. “C207-91(1997): Standard Specification for Hydrated Lime for Masonry Purposes.” *Annual Book of ASTM Standards*. West Conshohocken, PA: American Society for the Testing of Materials, 2001.

American Society for the Testing of Materials Standards. “C230/230M-98: Standard Specification for Flow Table for Use in Test of Hydraulic Cement.” *Annual Book of ASTM Standards*. West Conshohocken, PA: American Society for the Testing of Materials, 2001.

American Society for the Testing of Materials Standards. “C270-00: Standard Specification for Mortar for Unit Masonry.” *Annual Book of ASTM Standards*. West Conshohocken, PA: American Society for the Testing of Materials, 2001.

American Society for the Testing of Materials Standards. “C305-99: Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency.” *Annual Book of ASTM Standards*. West Conshohocken, PA: American Society for the Testing of Materials, 2001.

American Society for the Testing of Materials Standards. “C490-00a: Standard Practice for Use of Apparatus for the Determination of Length Change of Hardened Cement Paste, Mortar, and Concrete.” *Annual Book of ASTM Standards*. West Conshohocken, PA: American Society for the Testing of Materials, 2001.

American Society for the Testing of Materials Standards. “C511-98: Standard Specification for Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes.” *Annual Book of ASTM Standards*. West Conshohocken, PA: American Society for the Testing of Materials, 2001.

American Society for the Testing of Materials Standards. “C531-00: Standard Test Method for Linear Shrinkage and Coefficient of Thermal Expansion of Chemical-Resistant Mortars, Grouts, Monolithic Surfacings, and Polymer Concretes.” *Annual Book of ASTM Standards*. West Conshohocken, PA: American Society for the Testing of Materials, 2001.

American Society for the Testing of Materials Standards. “C580-98: Standard Test Method for Flexural Strength and Modulus of Elasticity of Chemical-Resistant Mortars, Grouts, Monolithic Surfacings, and Polymer Concretes.” *Annual Book of ASTM Standards*. West Conshohocken, PA: American Society for the Testing of Materials, 2001.

American Society for the Testing of Materials Standards. “C702-98: Standard Practice for Reducing Samples of Aggregate to Testing Size.” *Annual Book of ASTM Standards*. West Conshohocken, PA: American Society for the Testing of Materials, 2001.

American Society for the Testing of Materials Standards. “C1148-92a(1997): Standard Test Method for Measuring Drying Shrinkage of Masonry Mortar.” *Annual Book of ASTM Standards*. West Conshohocken, PA: American Society for the Testing of Materials, 2001.

American Society for the Testing of Materials Standards. “C1437-99: Standard Test Method for Flow of Hydraulic Cement Mortar.” *Annual Book of ASTM Standards*. West Conshohocken, PA: American Society for the Testing of Materials, 2001.

American Society for the Testing of Materials Standards. “E96-00: Standard Test Methods for Water Vapor Transmission of Materials.” *Annual Book of ASTM Standards*. West Conshohocken, PA: American Society for the Testing of Materials, 2001.

European Committee for Standardization. “EN 1015-3: 1995 E, Methods of Test for Mortar for Masonry - Part 3: Determination of Consistency of Fresh Mortar (by Flow Table).” Brussels: European Committee for Standardization, 1995.

NORMAL 7/81. *Water Absorption by Total Immersion – Imbibition Capacity*. Original in Italian, draft translation by A.E. Charola. Photocopy.

NORMAL 21/85. *Water Vapor Permeability*. Original in Italian, draft translation by A.E. Charola. Photocopy.

NORMAL 29/88. *Measurement of the Drying Index*. Original in Italian, draft translation by A.E. Charola. Photocopy.

RILEM V.II.7. “Linear Strain Due to Water Absorption.” *Materials and Structures,* vol. 13, no. 75 (1980).

RILEM V.1a. “Crystallization Test by Total Immersion (for Untreated Stone).” *Materials and Structures,* vol. 13, no. 75 (1980).

RILEM V.1b. “Crystallization Test by Total Immersion (for Treated Stone.” *Materials and Structures*, vol. 13, no. 75 (1980).

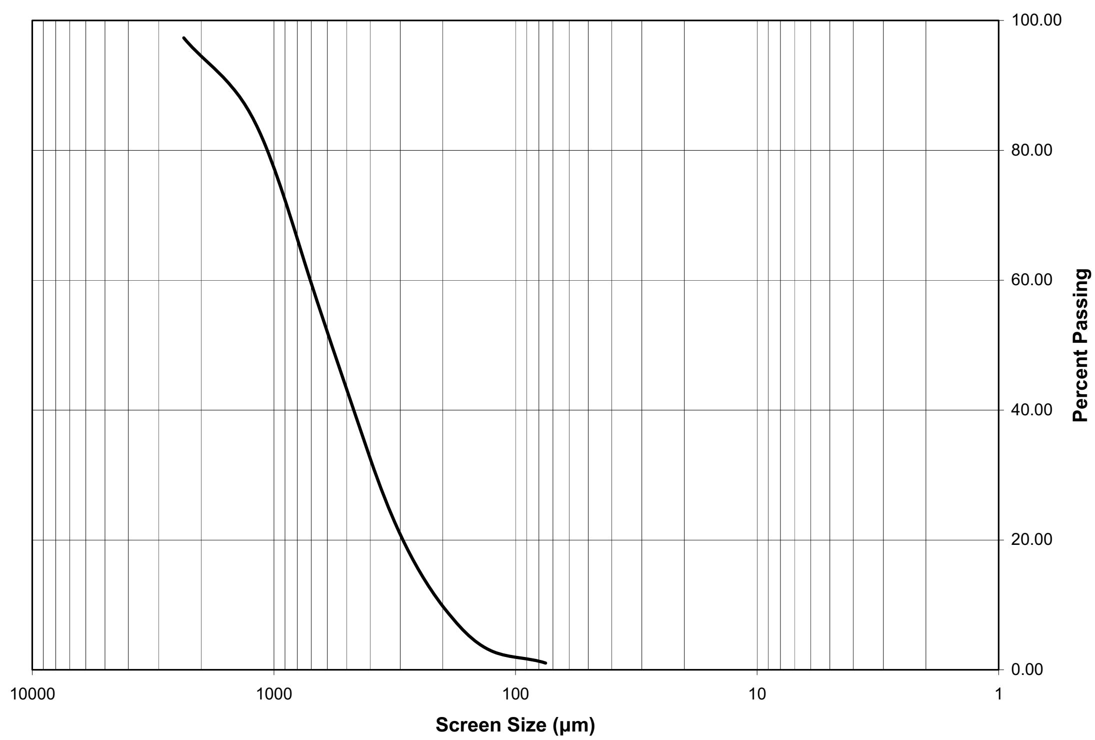
RILEM V.2. “Crystallization Test by Partial Immersion.” *Materials and Structures*, vol. 13, no. 75 (1980).

RILEM V.3. “Frost Resistance.” *Materials and Structures*, vol. 13, no. 75 (1980).

APPENDIX A: PARTICLE SIZE DISTRIBUTION OF FORMULATION SAND – ASTM C136-01

SCHOFIELD #236 RED MASON SAND

ASTM Sieve Number	Screen Size (μm)	Mass of container (g)	Mass of sample & container (g)	Mass retained (g)	Percent mass retained	Percent on or above	Percent Passing
8	2360	4.56	24.43	19.87	2.67	2.67	97.33
16	1180	4.58	104.95	100.37	13.51	16.19	83.81
30	600	4.58	241.07	236.49	31.84	48.02	51.98
50	300	4.68	235.84	231.16	31.12	79.14	20.86
100	150	4.65	124.47	119.82	16.13	95.27	4.73
200	75	4.67	32.12	27.45	3.70	98.96	1.04
Pan	0	4.77	11.91	7.14	0.96	99.92	0.08



APPENDIX B: SETTING TIME – ASTM C191-99

KEY TO SAMPLES IN ALL TESTS

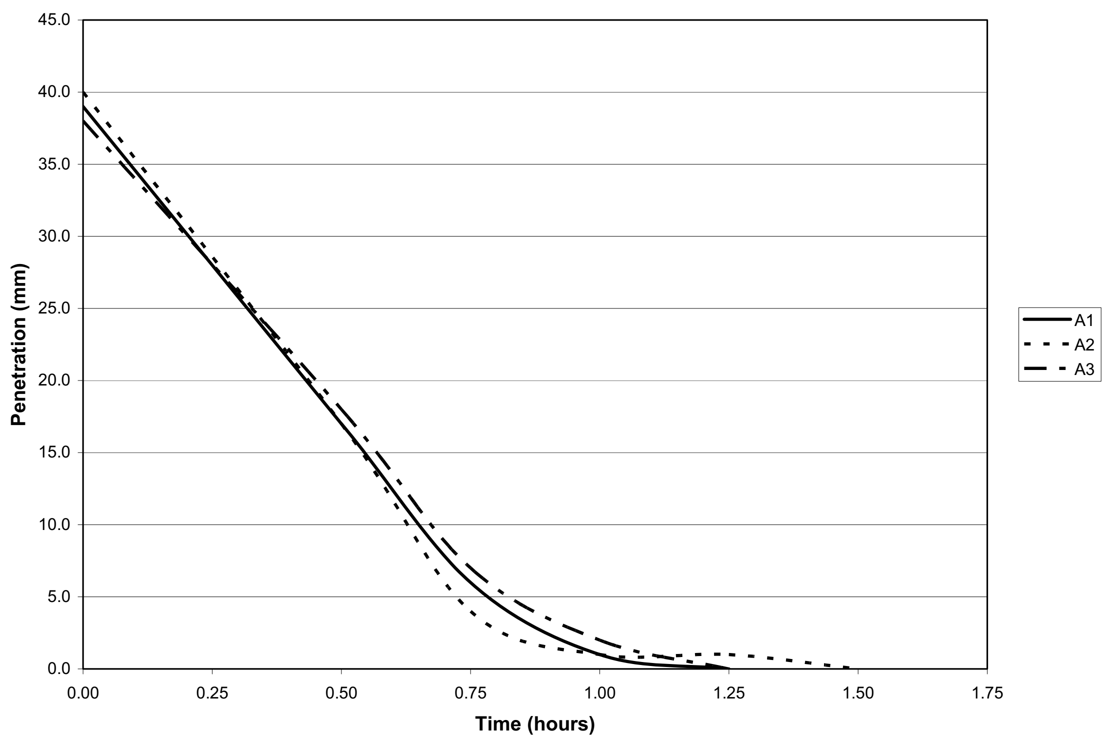
Group A	cement/lime putty mortars
Group B	cement/lime putty mortars with acrylic
Group C	feebly hydraulic lime mortars
Group D	feebly hydraulic lime mortars with acrylic
Group E	moderately hydraulic lime mortars
Group F	moderately hydraulic lime mortars with acrylic
Group S	Connecticut Brownstone

Appendix B: Setting Time – ASTM C191-99

Penetration Measurements (mm) for Cement/Lime Putty Samples

Time (hours)	Sample A1	Sample A2	Sample A3
0.50	17	17	18
0.75	6	4	7
1.00	1	1	2
1.25	0	1	0
1.50	---	0	---

Setting Time for Cement/Lime Putty Samples

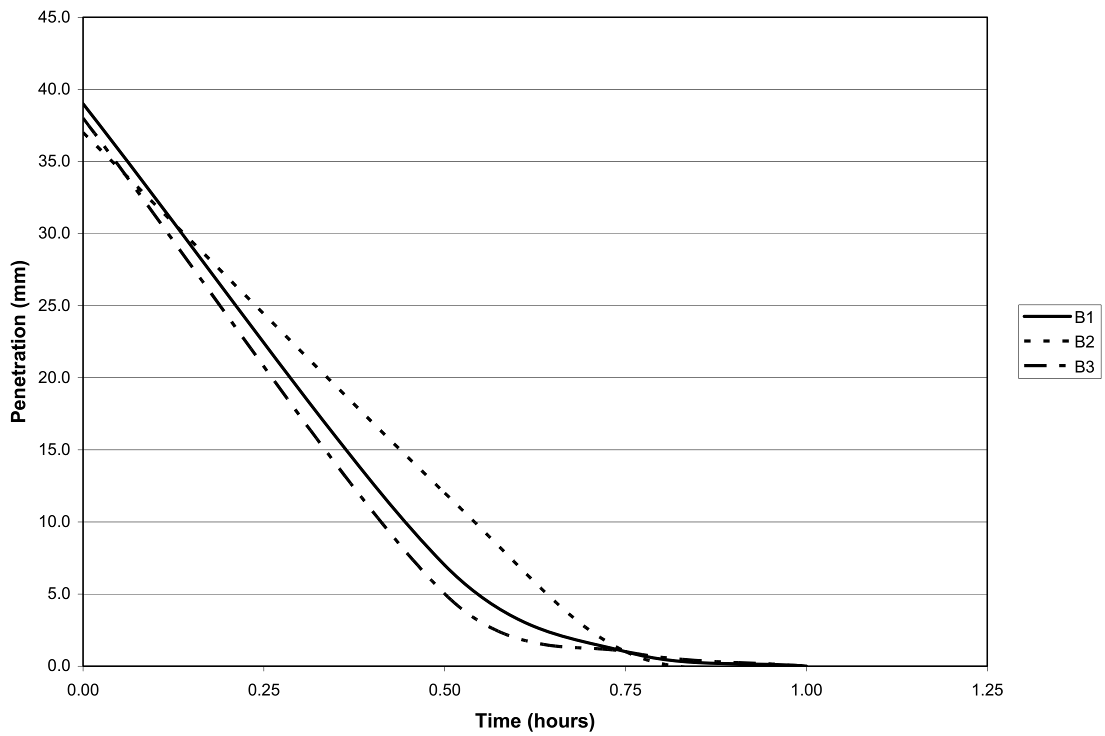


APPENDIX B: SETTING TIME – ASTM C191-99

PENETRATION MEASUREMENTS (MM)
FOR CEMENT/LIME PUTTY SAMPLES WITH ACRYLIC EMULSION

Time (hours)	Sample		
	B1	B2	B3
0.00	39	37	38
0.50	7	12	5
0.75	1	1	1
1.00	0	0	0

SETTING TIME FOR CEMENT/LIME PUTTY SAMPLES WITH ACRYLIC EMULSION



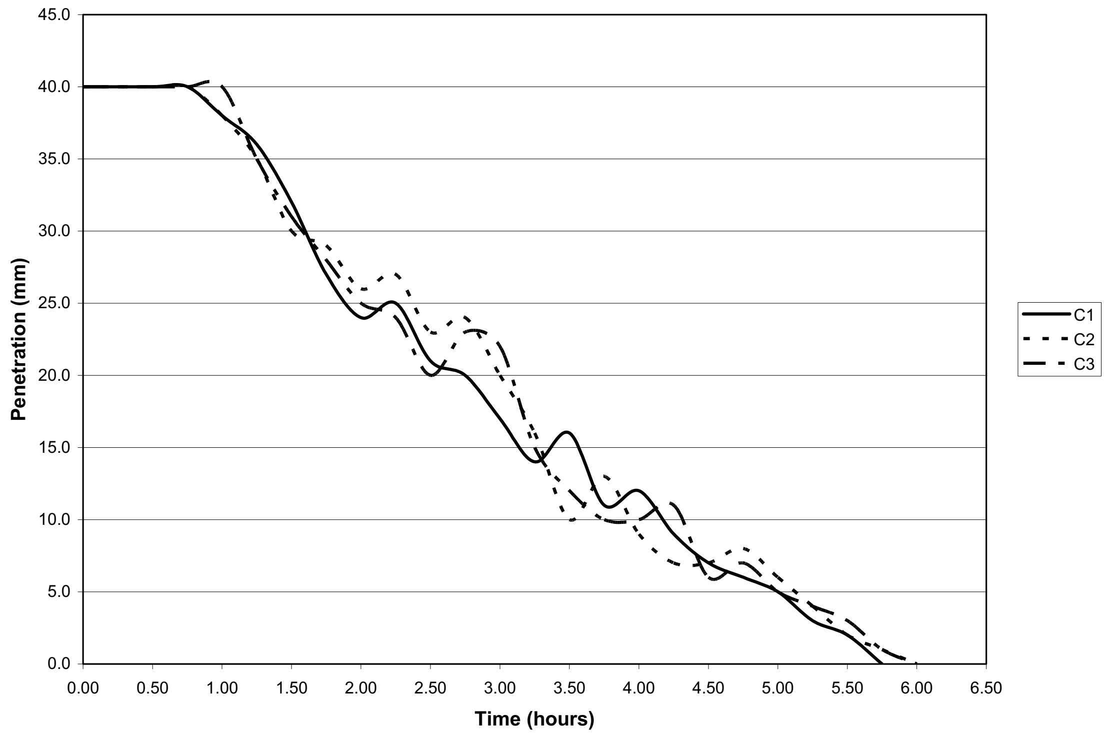
APPENDIX B: SETTING TIME – ASTM C191-99

PENETRATION MEASUREMENTS (MM)
FOR FEEBLY HYDRAULIC LIME SAMPLES

Time (hours)	Sample		
	C1	C2	C3
0.00	40	40	40
0.50	40	40	40
0.75	40	40	40
1.00	38	38	40
1.25	36	35	35
1.50	32	30	31
1.75	27	29	28
2.00	24	26	25
2.25	25	27	24
2.50	21	23	20
2.75	20	24	23
3.00	17	20	22
3.25	14	16	15
3.50	16	10	12
3.75	11	13	10
4.00	12	9	10
4.25	9	7	11
4.50	7	7	6
4.75	6	8	7
5.00	5	6	5
5.25	3	4	4
5.50	2	2	3
5.75	0	1	1
6.00	---	0	0

APPENDIX B: SETTING TIME – ASTM C191-99

SETTING TIME FOR FEEBLY HYDRAULIC LIME SAMPLES



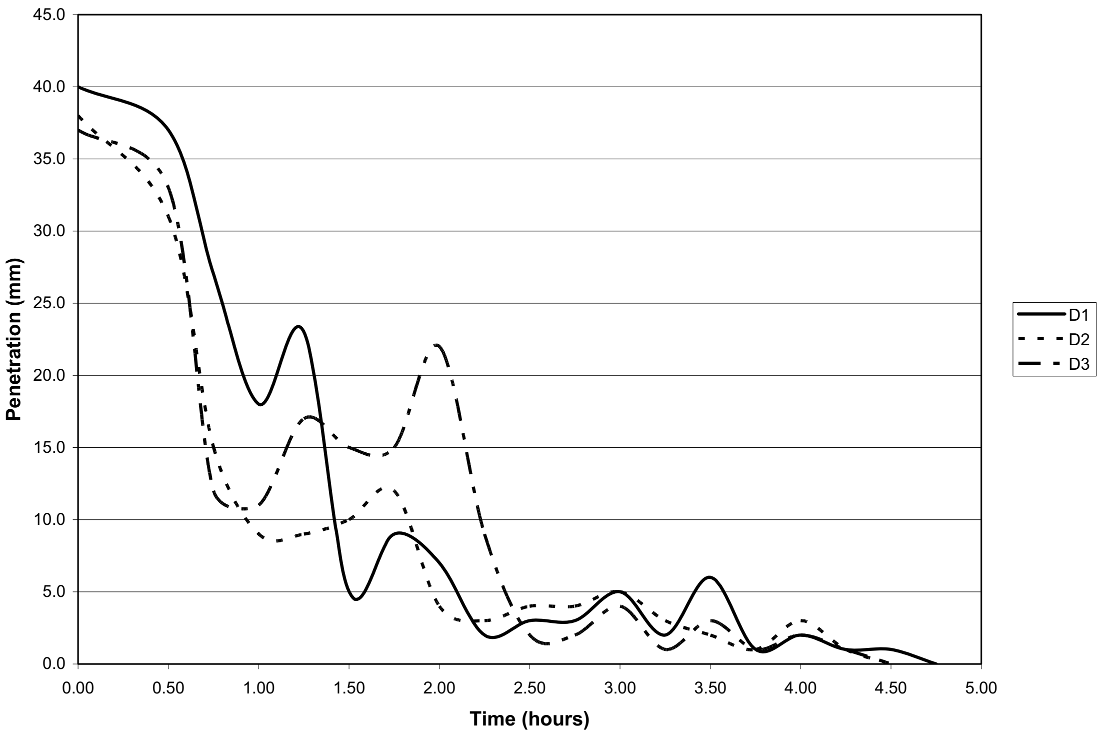
APPENDIX B: SETTING TIME – ASTM C191-99

PENETRATION MEASUREMENTS (MM)
FOR FEEBLY HYDRAULIC LIME SAMPLES WITH ACRYLIC EMULSION

Time (hours)	Sample		
	D1	D2	D3
0.00	40	38	37
0.50	37	31	33
0.75	27	15	12
1.00	18	9	11
1.25	23	9	17
1.50	5	10	15
1.75	9	12	15
2.00	7	4	22
2.25	2	3	9
2.50	3	4	2
2.75	3	4	2
3.00	5	5	4
3.25	2	3	1
3.50	6	2	3
3.75	1	1	1
4.00	2	3	2
4.25	1	1	1
4.50	1	0	0
4.75	0	---	---

APPENDIX B: SETTING TIME – ASTM C191-99

SETTING TIME FOR FEEBLY HYDRAULIC LIME SAMPLES WITH ACRYLIC EMULSION



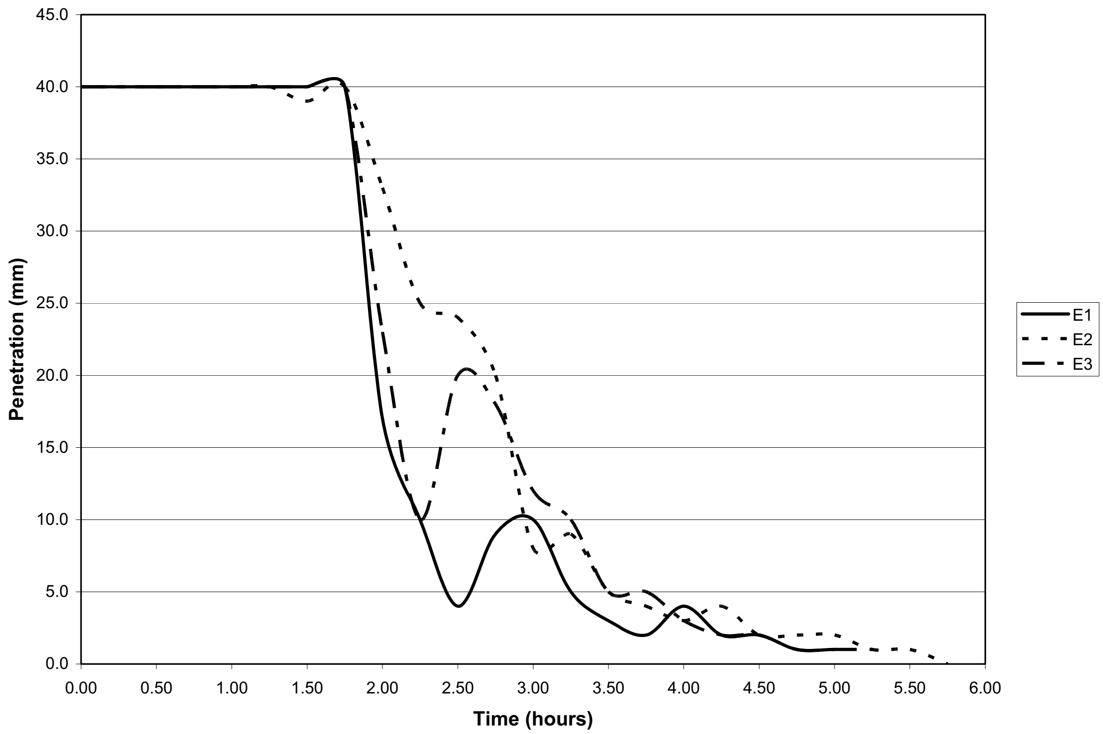
APPENDIX B: SETTING TIME – ASTM C191-99

PENETRATION MEASUREMENTS (MM)
FOR MODERATELY HYDRAULIC LIME SAMPLES

Time (hours)	Sample		
	E1	E2	E3
0.00	40	40	40
0.50	40	40	40
0.75	40	40	40
1.00	40	40	40
1.25	40	40	40
1.50	40	39	40
1.75	40	40	40
2.00	17	33	23
2.25	10	25	10
2.50	4	24	20
2.75	9	20	18
3.00	10	8	12
3.25	5	9	10
3.50	3	5	5
3.75	2	4	5
4.00	4	3	3
4.25	2	4	2
4.50	2	2	2
4.75	1	2	1
5.00	1	2	1
5.25	0	1	1
5.50	---	1	0
5.75	---	0	---

APPENDIX B: SETTING TIME – ASTM C191-99

SETTING TIME FOR MODERATELY HYDRAULIC LIME SAMPLES



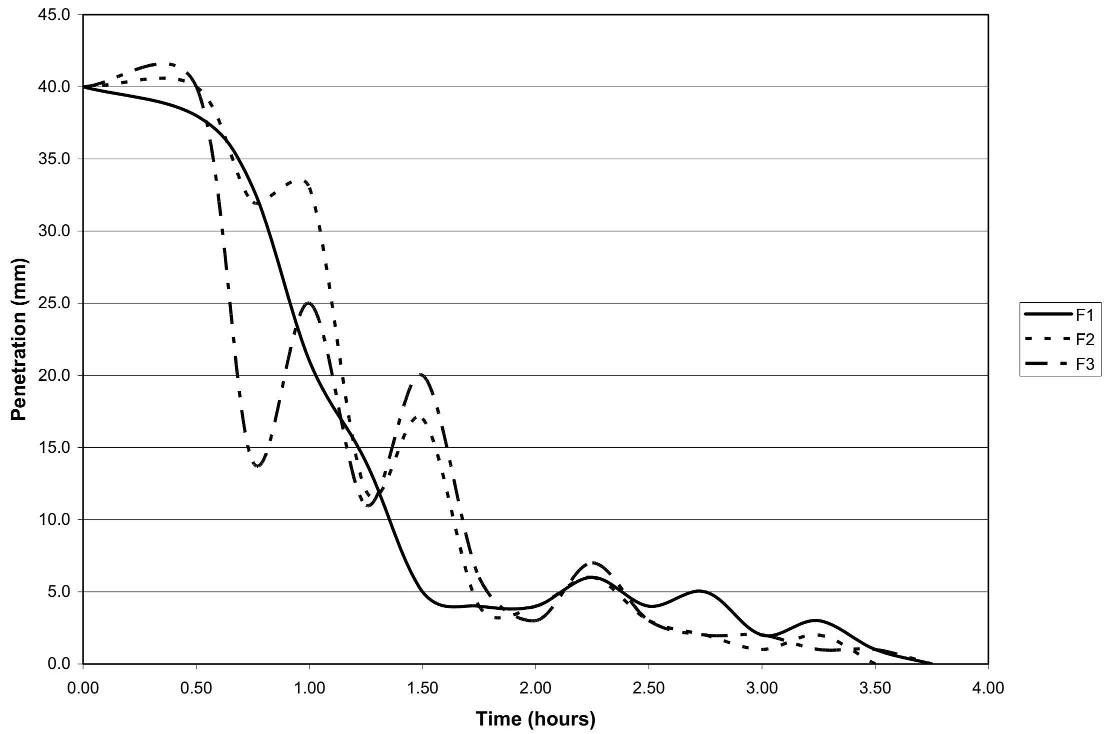
APPENDIX B: SETTING TIME – ASTM C191-99

PENETRATION MEASUREMENTS (MM)
FOR MODERATELY HYDRAULIC LIME SAMPLES WITH ACRYLIC EMULSION

Time (hours)	Sample		
	F1	F2	F3
0.00	40	40	40
0.50	38	40	40
0.75	33	32	14
1.00	21	33	25
1.25	14	12	11
1.50	5	17	20
1.75	4	4	6
2.00	4	4	3
2.25	6	6	7
2.50	4	3	3
2.75	5	2	2
3.00	2	1	2
3.25	3	2	1
3.50	1	0	1
3.75	0	---	0

APPENDIX B: SETTING TIME – ASTM C191-99

SETTING TIME FOR MODERATELY HYDRAULIC LIME SAMPLES WITH ACRYLIC EMULSION



APPENDIX C: DRYING SHRINKAGE – ASTM C1148-97

LENGTH COMPARATOR MEASUREMENTS (INCH)

Sample	Days				
	0	4	11	18	25
A1	0.2057	0.2023	0.2023	0.2011	0.2010
A2	0.2061	0.2032	0.2031	0.2020	0.2017
A3	0.2031	0.2005	0.2001	0.1991	0.1990
B1	0.2051	0.2022	0.2022	0.2014	0.2012
B2	0.2128	0.2105	0.2100	0.2089	0.2088
B3	0.2097	0.2069	0.2064	0.2054	0.2053
C1	0.2028	0.2007	0.2007	0.2004	0.2003
C2	0.2042	0.2032	0.2032	0.2029	0.2029
C3	sample broke when demolded				
D1	0.2046	0.2031	0.2031	0.2026	0.2024
D2	sample broke when demolded				
D3	sample broke when demolded				
E1	0.2110	0.2079	0.2024	0.2020	0.2019
E2	0.2132	0.2108	0.2104	0.2098	0.2094
E3	0.2102	0.2069	0.2070	0.2065	0.2064
F1	0.2067	0.2050	0.2044	0.2040	0.2037
F2	sample broke when demolded				
F3	sample broke when demolded				

Key to Samples	
Group A	cement/lime putty mortars
Group B	cement/lime putty mortars with acrylic
Group C	feebly hydraulic lime mortars
Group D	feebly hydraulic lime mortars with acrylic
Group E	moderately hydraulic lime mortars
Group F	moderately hydraulic lime mortars with acrylic

APPENDIX C: DRYING SHRINKAGE – ASTM C1148-97

LENGTH CALCULATIONS (INCHES)

Sample	Days				
	0	**4**	**11**	**18**	**25**
A1	6.6307	6.6273	6.6273	6.6261	6.6260
A2	6.6311	6.6282	6.6281	6.6270	6.6267
A3	6.6281	6.6255	6.6251	6.6241	6.6240
B1	6.6301	6.6272	6.6272	6.6264	6.6262
B2	6.6378	6.6355	6.6350	6.6339	6.6338
B3	6.6347	6.6319	6.6314	6.6304	6.6303
C1	6.6278	6.6257	6.6257	6.6254	6.6253
C2	6.6292	6.6282	6.6282	6.6279	6.6279
C3	sample broke when demolded				
D1	6.6296	6.6281	6.6281	6.6276	6.6274
D2	sample broke when demolded				
D3	sample broke when demolded				
E1	6.6360	6.6329	6.6274	6.6270	6.6269
E2	6.6382	6.6358	6.6354	6.6348	6.6344
E3	6.6352	6.6319	6.6320	6.6315	6.6314
F1	6.6317	6.6300	6.6294	6.6290	6.6287
F2	sample broke when demolded				
F3	sample broke when demolded				

Key to Samples	
Group A	cement/lime putty mortars
Group B	cement/lime putty mortars with acrylic
Group C	feebly hydraulic lime mortars
Group D	feebly hydraulic lime mortars with acrylic
Group E	moderately hydraulic lime mortars
Group F	moderately hydraulic lime mortars with acrylic

APPENDIX D: THERMAL EXPANSION – ASTM 531-00

LENGTH COMPARATOR MEASUREMENTS AND LENGTH CALCULATIONS

Sample	Reference bar length (in)	Reference bar reading	Sample reading at 83°F	Sample length including studs at 83°F, W (in)	Sample reading at 210°F	Sample length including studs at 210°F, Z (in)
A1	6.6250	0.2000	0.2416	6.6666	0.2457	6.6707
A2	6.6250	0.2000	0.2027	6.6277	0.2063	6.6313
A3	6.6250	0.2000	0.2371	6.6621	0.2412	6.6662
B1	6.6250	0.2000	0.2353	6.6603	0.2397	6.6647
B2	6.6250	0.2000	0.2085	6.6335	0.2123	6.6373
B3	6.6250	0.2000	0.2293	6.6543	0.2339	6.6589
C1	6.6250	0.2000	0.2197	6.6447	0.2242	6.6492
C2	sample broke during cure					
C3	sample broke during cure					
D1	6.6250	0.2000	0.2074	6.6324	0.2115	6.6365
D2	6.6250	0.2000	0.1813	6.6063	0.1861	6.6111
D3	6.6250	0.2000	0.1993	6.6243	0.2039	6.6289
E1	6.6250	0.2000	0.2356	6.6606	0.2409	6.6659
E2	6.6250	0.2000	0.2275	6.6525	0.2324	6.6574
E3	6.6250	0.2000	0.2251	6.6501	0.2294	6.6544
F1	6.6250	0.2000	0.2455	6.6705	0.2503	6.6753
F2	6.6250	0.2000	0.2247	6.6497	0.2297	6.6547
F3	6.6250	0.2000	0.2596	6.6846	0.2634	6.6884
S1	6.6250	0.2000	0.2756	6.7006	0.2813	6.7063
S2	6.6250	0.2000	0.2529	6.6779	0.2589	6.6839
S3	enough stone was available for only two samples					

Key to Samples	
Group A	cement/lime putty mortars
Group B	cement/lime putty mortars with acrylic
Group C	feebly hydraulic lime mortars
Group D	feebly hydraulic lime mortars with acrylic
Group E	moderately hydraulic lime mortars
Group F	moderately hydraulic lime mortars with acrylic
Group S	Connecticut brownstone

APPENDIX D: THERMAL EXPANSION – ASTM 531-00

COEFFICIENT OF THERMAL EXPANSION CALCULATIONS

Sample	Sample length including studs at 83°F, W (in)	Sample length including studs at 210°F, Z (in)	Length of 2 studs at 83°F, X (in)	Temp change, T (°F)	Coefficient of thermal expansion of studs, k (in/in·°F)	Stud expansion, Y (in)	Coefficient of thermal expansion of sample (in/in·°F)
A1	6.6666	6.6707	1.6250	127	8.80E-06	1.82E-03	3.57E-06
A2	6.6277	6.6313	1.6250	127	8.80E-06	1.82E-03	2.81E-06
A3	6.6621	6.6662	1.6250	127	8.80E-06	1.82E-03	3.57E-06
B1	6.6603	6.6647	1.6250	127	8.80E-06	1.82E-03	4.04E-06
B2	6.6335	6.6373	1.6250	127	8.80E-06	1.82E-03	3.12E-06
B3	6.6543	6.6589	1.6250	127	8.80E-06	1.82E-03	4.36E-06
C1	6.6447	6.6492	1.6250	127	8.80E-06	1.82E-03	4.21E-06
C2	sample broke during cure						
C3	sample broke during cure						
D1	6.6324	6.6365	1.6250	127	8.80E-06	1.82E-03	3.59E-06
D2	6.6063	6.6111	1.6250	127	8.80E-06	1.82E-03	4.72E-06
D3	6.6243	6.6289	1.6250	127	8.80E-06	1.82E-03	4.38E-06
E1	6.6606	6.6659	1.6250	127	8.80E-06	1.82E-03	5.45E-06
E2	6.6525	6.6574	1.6250	127	8.80E-06	1.82E-03	4.83E-06
E3	6.6501	6.6544	1.6250	127	8.80E-06	1.82E-03	3.89E-06
F1	6.6705	6.6753	1.6250	127	8.80E-06	1.82E-03	4.66E-06
F2	6.6497	6.6547	1.6250	127	8.80E-06	1.82E-03	4.99E-06
F3	6.6846	6.6884	1.6250	127	8.80E-06	1.82E-03	3.09E-06
S1	6.7006	6.7063	1.6250	127	8.80E-06	1.82E-03	6.03E-06
S2	6.6779	6.6839	1.6250	127	8.80E-06	1.82E-03	6.52E-06
S3	enough stone was available for only two samples						

Key to Samples	
Group A	cement/lime putty mortars
Group B	cement/lime putty mortars with acrylic
Group C	feebly hydraulic lime mortars
Group D	feebly hydraulic lime mortars with acrylic
Group E	moderately hydraulic lime mortars
Group F	moderately hydraulic lime mortars with acrylic
Group S	Connecticut brownstone

Appendix E: Linear Strain Due To Water Absorption – RILEM II.7

Length Comparator Measurements (Inch)

Sample	Hours										
	0	**0.5**	**1**	**2**	**4**	**8**	**24**	**48**	**72**	**96**	**120**
A1	0.2413	0.2421	0.2422	0.2424	0.2425	0.2429	0.2432	0.2435	0.2437	0.2439	0.2439
A2	0.2022	0.2033	0.2034	0.2034	0.2035	0.2039	0.2045	0.2047	0.2048	0.2050	0.2050
A3	0.2368	0.2375	0.2379	0.2382	0.2383	0.2383	0.2389	0.2391	0.2392	0.2393	0.2393
B1	0.2349	0.2362	0.2364	0.2367	0.2367	0.2370	0.2374	0.2377	0.2378	0.2379	0.2379
B2	0.2081	0.2091	0.2093	0.2093	0.2096	0.2098	0.2102	0.2103	0.2104	0.2106	0.2106
B3	0.2292	0.2303	0.2305	0.2306	0.2307	0.2310	0.2312	0.2319	0.2320	0.2319	0.2319
C1	0.2189	0.2193	0.2198	0.2194	0.2197	0.2194	0.2198	0.2196	0.2195	0.2190	0.2193
C2	sample broke during cure										
C3	sample broke during cure										
D1	0.2068	0.2071	0.2070	0.2070	0.2074	0.2072	0.2073	0.2071	0.2071	0.2071	0.2071
D2	0.1814	0.1814	0.1816	0.1814	0.1815	0.1816	0.1820	0.1821	0.1822	0.1819	0.1820
D3	0.1892	0.1895	0.1894	0.1896	0.1895	0.1897	0.1897	0.1899	0.1900	0.1900	0.1900
E1	0.2357	0.2358	0.2357	0.2358	0.2358	0.2357	0.2358	0.2359	0.2360	0.2359	0.2360
E2	0.2274	0.2280	0.2277	0.2281	0.2281	0.2282	0.2284	0.2284	0.2285	0.2286	0.2286
E3	0.2247	0.2253	0.2252	0.2252	0.2251	0.2253	0.2254	0.2257	0.2258	0.2255	0.2256
F1	0.2454	0.2454	0.2454	0.2454	0.2455	0.2455	0.2457	0.2459	0.2460	0.2461	0.2461
F2	0.2248	0.2249	0.2251	0.2251	0.2253	0.2254	0.2255	0.2255	0.2257	0.2256	0.2258
F3	0.2585	0.2587	0.2591	0.2589	0.2589	0.2590	0.2592	0.2594	0.2595	0.2594	0.2594
S1	0.2752	0.2755	0.2758	0.2765	0.2764	0.2767	0.2767	0.2768	0.2769	0.2770	0.2770
S2	0.2530	0.2533	0.2535	0.2537	0.2540	0.2545	0.2546	0.2545	0.2546	0.2550	0.2549
S3	enough stone was available for only two samples										

Appendix E: Linear Strain Due To Water Absorption – RILEM II.7

Length Change Calculations (Inch)

Sample	Hours										
	0	0.5	1	2	4	8	24	48	72	96	120
A1	0.0000	0.0008	0.0009	0.0011	0.0012	0.0016	0.0019	0.0022	0.0024	0.0026	0.0026
A2	0.0000	0.0011	0.0012	0.0012	0.0013	0.0017	0.0023	0.0025	0.0026	0.0028	0.0028
A3	0.0000	0.0007	0.0011	0.0014	0.0015	0.0015	0.0021	0.0023	0.0024	0.0025	0.0025
B1	0.0000	0.0013	0.0015	0.0018	0.0018	0.0021	0.0025	0.0028	0.0029	0.0030	0.0030
B2	0.0000	0.0010	0.0012	0.0012	0.0015	0.0017	0.0021	0.0022	0.0023	0.0025	0.0025
B3	0.0000	0.0011	0.0013	0.0014	0.0015	0.0018	0.0020	0.0027	0.0028	0.0027	0.0027
C1	0.0000	0.0004	0.0009	0.0005	0.0008	0.0005	0.0009	0.0007	0.0006	0.0001	0.0004
C2	sample broke during cure										
C3	sample broke during cure										
D1	0.0000	0.0003	0.0002	0.0002	0.0006	0.0004	0.0005	0.0003	0.0003	0.0003	0.0003
D2	0.0000	0.0000	0.0002	0.0000	0.0001	0.0002	0.0006	0.0007	0.0008	0.0005	0.0006
D3	0.0000	0.0003	0.0002	0.0004	0.0003	0.0005	0.0005	0.0007	0.0008	0.0008	0.0008
E1	0.0000	0.0001	0.0000	0.0001	0.0001	0.0000	0.0001	0.0002	0.0003	0.0002	0.0003
E2	0.0000	0.0006	0.0003	0.0007	0.0007	0.0008	0.0010	0.0010	0.0011	0.0012	0.0012
E3	0.0000	0.0006	0.0005	0.0005	0.0004	0.0006	0.0007	0.0010	0.0011	0.0008	0.0009
F1	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0003	0.0005	0.0006	0.0007	0.0007
F2	0.0000	0.0001	0.0003	0.0003	0.0005	0.0006	0.0007	0.0007	0.0009	0.0008	0.0010
F3	0.0000	0.0002	0.0006	0.0004	0.0004	0.0005	0.0007	0.0009	0.0010	0.0009	0.0009
S1	0.0000	0.0003	0.0006	0.0013	0.0012	0.0015	0.0015	0.0016	0.0017	0.0018	0.0018
S2	0.0000	0.0003	0.0005	0.0007	0.0010	0.0015	0.0016	0.0015	0.0016	0.0020	0.0019
S3	enough stone was available for only two samples										

Appendix E: Linear Strain Due To Water Absorption – RILEM II.7

Linear Strain Calculations (Inch/Inch)

Sample	Hours					
	0	0.5	1	2	4	8
A1	0.00E+00	1.20E-04	1.35E-04	1.65E-04	1.80E-04	2.40E-04
A2	0.00E+00	1.66E-04	1.81E-04	1.81E-04	1.96E-04	2.56E-04
A3	0.00E+00	1.05E-04	1.65E-04	2.10E-04	2.25E-04	2.25E-04
B1	0.00E+00	1.95E-04	2.25E-04	2.70E-04	2.70E-04	3.15E-04
B2	0.00E+00	1.51E-04	1.81E-04	1.81E-04	2.26E-04	2.56E-04
B3	0.00E+00	1.65E-04	1.95E-04	2.10E-04	2.25E-04	2.70E-04
C1	0.00E+00	6.02E-05	1.35E-04	7.53E-05	1.20E-04	7.53E-05
C2	sample broke during cure					
C3	sample broke during cure					
D1	0.00E+00	4.52E-05	3.02E-05	3.02E-05	9.05E-05	6.03E-05
D2	0.00E+00	0.00E+00	3.03E-05	0.00E+00	1.51E-05	3.03E-05
D3	0.00E+00	4.54E-05	3.02E-05	6.05E-05	4.54E-05	7.56E-05
E1	0.00E+00	1.50E-05	0.00E+00	1.50E-05	1.50E-05	0.00E+00
E2	0.00E+00	9.02E-05	4.51E-05	1.05E-04	1.05E-04	1.20E-04
E3	0.00E+00	9.02E-05	7.52E-05	7.52E-05	6.01E-05	9.02E-05
F1	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.50E-05	1.50E-05
F2	0.00E+00	1.50E-05	4.51E-05	4.51E-05	7.52E-05	9.02E-05
F3	0.00E+00	2.99E-05	8.98E-05	5.98E-05	5.98E-05	7.48E-05
S1	0.00E+00	4.48E-05	8.95E-05	1.94E-04	1.79E-04	2.24E-04
S2	0.00E+00	4.49E-05	7.49E-05	1.05E-04	1.50E-04	2.25E-04
S3	enough stone was available for only two samples					

Appendix E: Linear Strain Due To Water Absorption – RILEM II.7

Linear Strain Calculations (Inch/Inch)

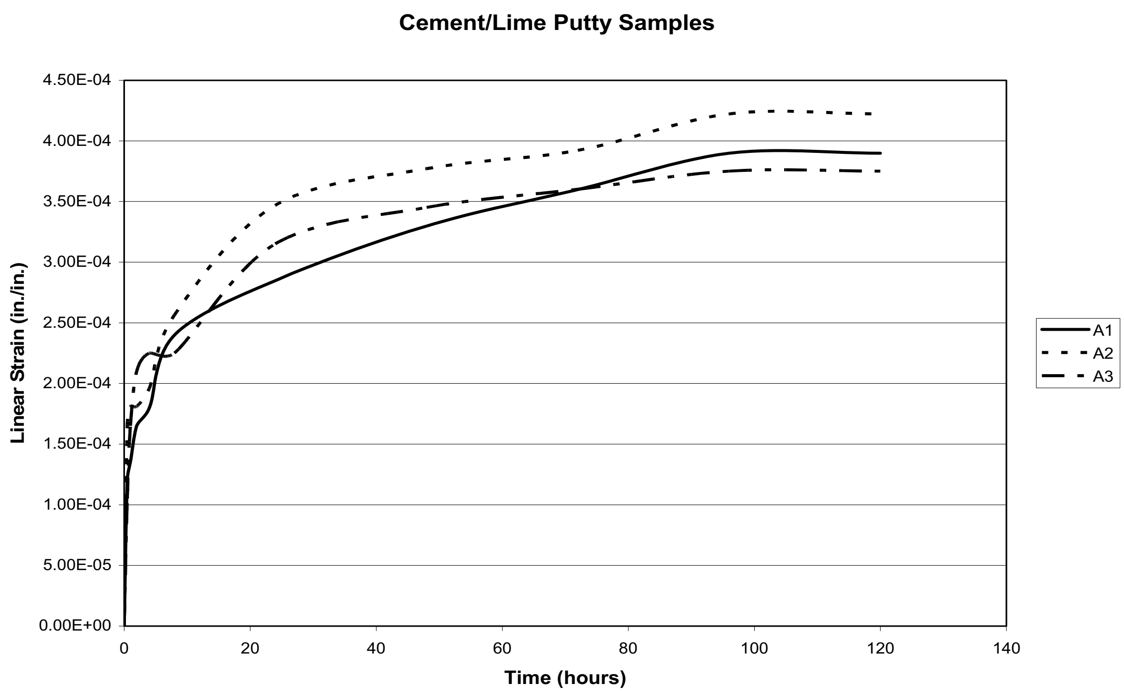
Sample	Hours				
	24	48	72	96	120
A1	2.85E-04	3.30E-04	3.60E-04	3.90E-04	3.90E-04
A2	3.47E-04	3.77E-04	3.92E-04	4.22E-04	4.22E-04
A3	3.15E-04	3.45E-04	3.60E-04	3.75E-04	3.75E-04
B1	3.75E-04	4.20E-04	4.35E-04	4.50E-04	4.50E-04
B2	3.16E-04	3.32E-04	3.47E-04	3.77E-04	3.77E-04
B3	3.00E-04	4.06E-04	4.21E-04	4.06E-04	4.06E-04
C1	1.35E-04	1.05E-04	9.03E-05	1.51E-05	6.02E-05
C2	sample broke during cure				
C3	sample broke during cure				
D1	7.54E-05	4.52E-05	4.52E-05	4.52E-05	4.52E-05
D2	9.08E-05	1.06E-04	1.21E-04	7.57E-05	9.08E-05
D3	7.56E-05	1.06E-04	1.21E-04	1.21E-04	1.21E-04
E1	1.50E-05	3.00E-05	4.50E-05	3.00E-05	4.50E-05
E2	1.50E-04	1.50E-04	1.65E-04	1.80E-04	1.80E-04
E3	1.05E-04	1.50E-04	1.65E-04	1.20E-04	1.35E-04
F1	4.50E-05	7.50E-05	8.99E-05	1.05E-04	1.05E-04
F2	1.05E-04	1.05E-04	1.35E-04	1.20E-04	1.50E-04
F3	1.05E-04	1.35E-04	1.50E-04	1.35E-04	1.35E-04
S1	2.24E-04	2.39E-04	2.54E-04	2.69E-04	2.69E-04
S2	2.40E-04	2.25E-04	2.40E-04	2.99E-04	2.84E-04
S3	enough stone was available for only two samples				

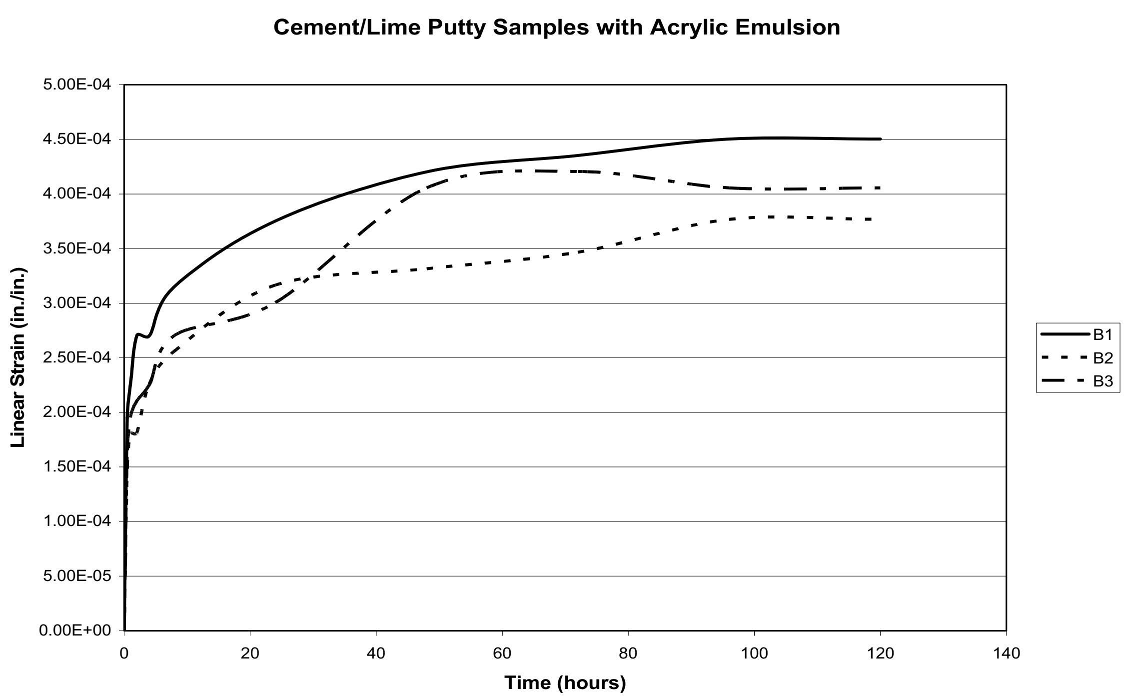
Key to Samples

Group A	cement/lime putty mortars
Group B	cement/lime putty mortars with acrylic
Group C	feebly hydraulic lime mortars
Group D	feebly hydraulic lime mortars with acrylic
Group E	moderately hydraulic lime mortars
Group F	moderately hydraulic lime mortars with acrylic
Group S	Connecticut brownstone

APPENDIX E: LINEAR STAIN DUE TO WATER ABSORPTION – RILEM II.7

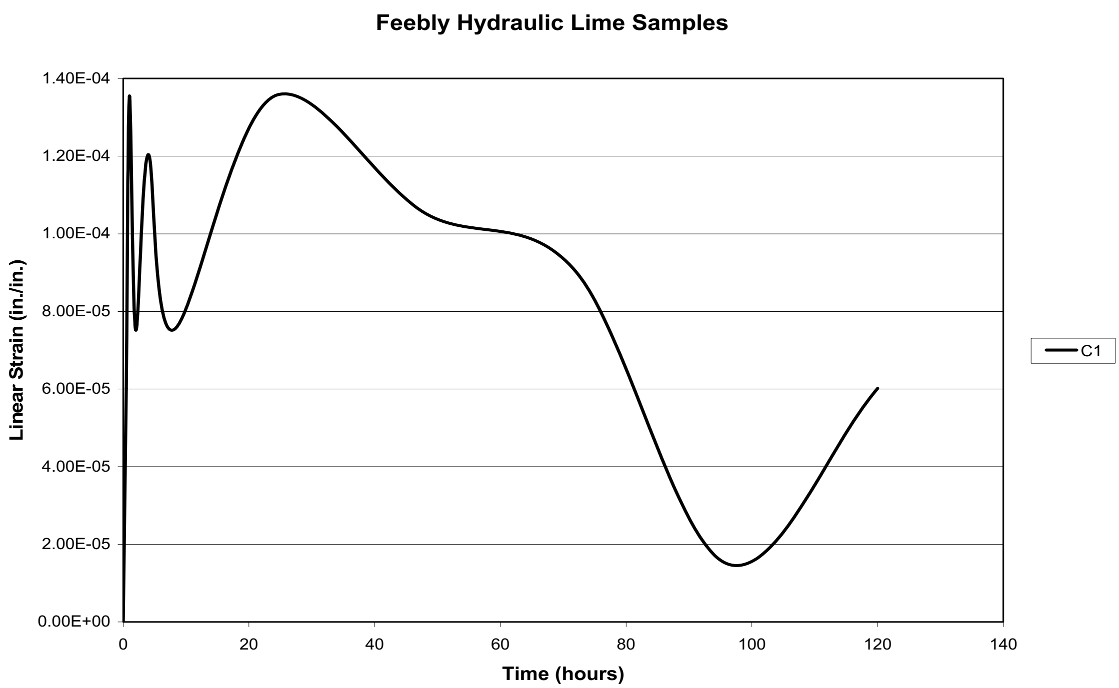
LINEAR STRAIN CURVES

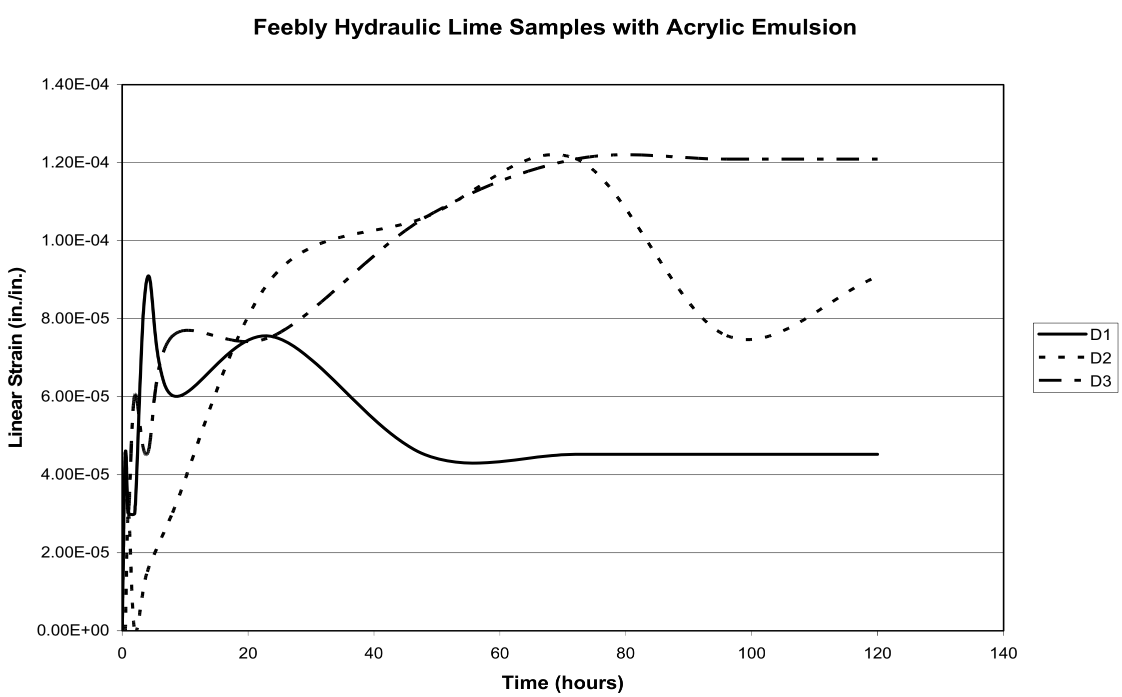




APPENDIX E: LINEAR STAIN DUE TO WATER ABSORPTION – RILEM II.7

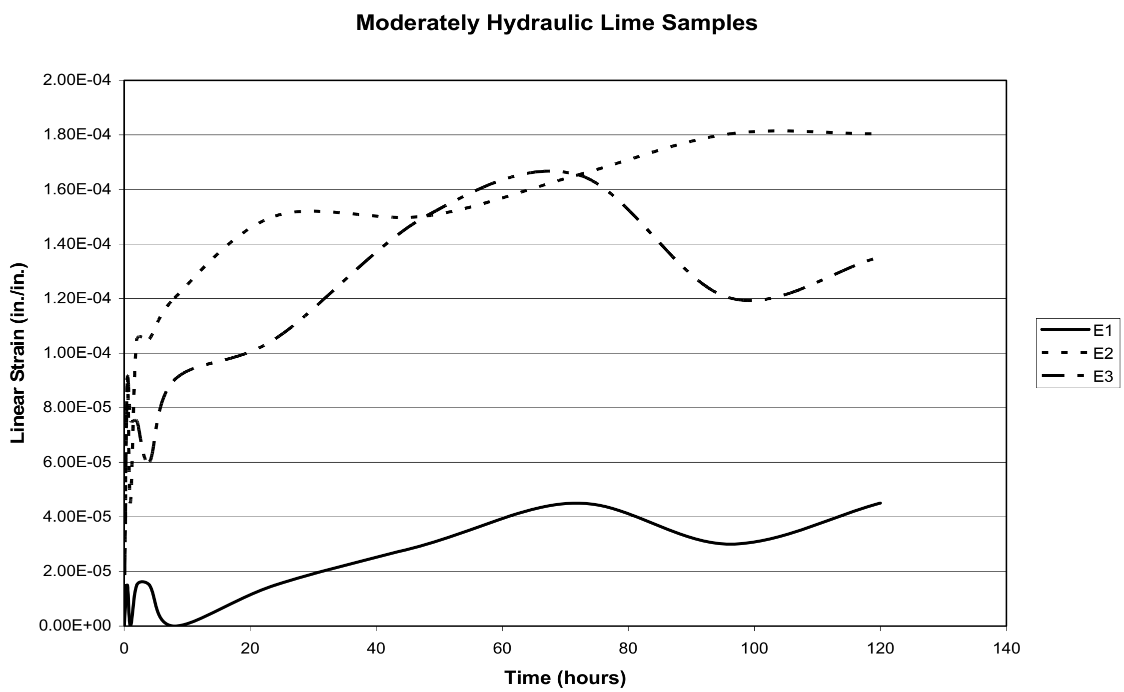
LINEAR STRAIN CURVES

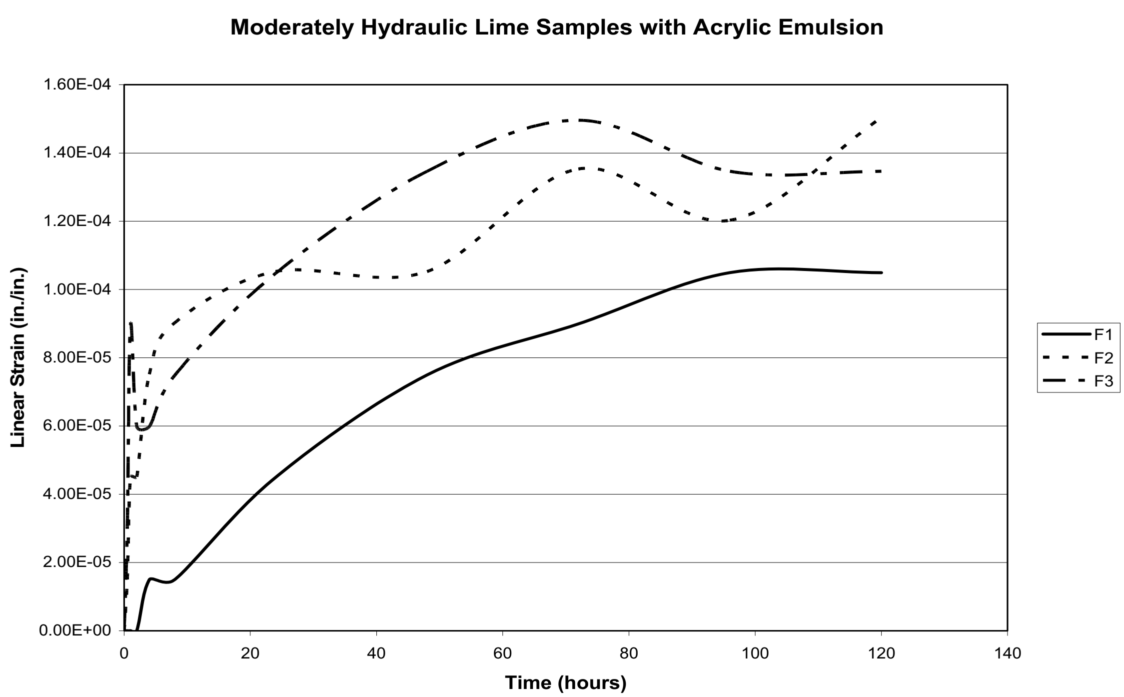




APPENDIX E: LINEAR STAIN DUE TO WATER ABSORPTION – RILEM II.7

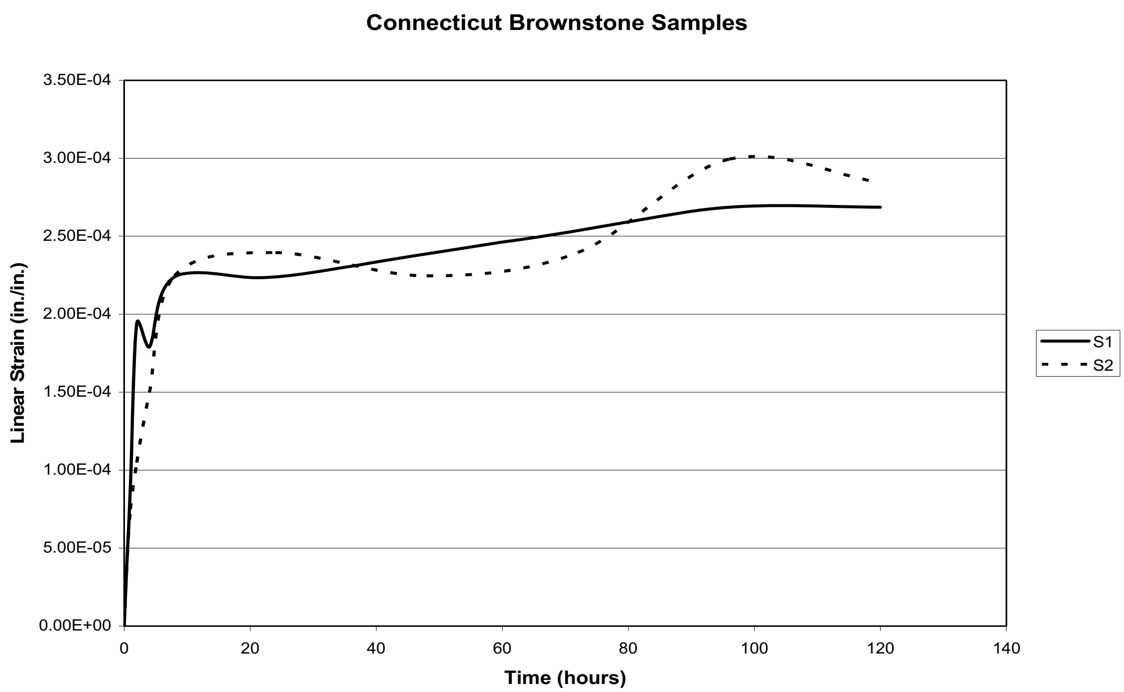
LINEAR STRAIN CURVES





APPENDIX E: LINEAR STAIN DUE TO WATER ABSORPTION – RILEM II.7

LINEAR STRAIN CURVES



APPENDIX F: WATER VAPOR TRANSMISSION – ASTM E96-00

Experiment Conditions
Temperature: 31°C
Relative Humidity: 50%
Water Vapor Partial Pressure: 33.72 mm Hg

Samples
0.013 m^2
1.3 cm in height
3 samples in each set

DAILY WEIGHT MEASUREMENTS (GRAMS)

Sample	Days										
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
A1	72.33	72.22	72.08	71.94	71.79	71.65	71.50	71.34	71.18	71.04	70.93
A2	72.06	71.95	71.81	71.68	71.53	71.39	71.21	71.08	70.92	70.80	70.68
A3	68.23	68.11	67.97	67.82	67.67	67.53	67.37	67.20	67.05	66.91	66.78
B1	72.58	72.48	72.35	72.21	72.08	71.94	71.80	71.65	71.51	71.38	71.25
B2	75.06	74.99	74.88	74.79	74.67	74.56	74.45	74.32	74.21	74.10	74.01
B3	74.47	74.41	74.33	74.22	74.13	74.03	73.92	73.81	73.70	73.61	73.52
C1	70.52	70.23	69.97	69.70	69.41	68.40	68.10	67.80	67.50	67.25	67.03
C2	67.21	66.89	66.60	66.31	66.00	65.70	65.38	65.04	64.71	64.44	64.18
C3	71.51	71.24	70.99	70.75	70.48	70.23	69.97	69.68	69.41	69.17	68.96
D1	71.05	70.82	70.61	70.41	70.20	69.99	69.77	69.53	69.31	69.10	68.91
D2	73.83	73.63	73.35	73.25	73.07	72.87	72.67	72.46	72.24	72.06	71.90
D3	74.07	73.82	73.59	73.38	73.15	72.92	72.69	72.43	72.19	71.96	71.77
E1	73.25	73.01	72.77	72.56	72.35	72.12	71.89	71.64	71.41	71.17	70.99
E2	75.55	75.32	75.09	74.89	74.67	74.46	74.24	74.00	73.76	73.55	73.37
E3	74.90	74.64	74.39	74.16	73.92	73.69	73.44	73.18	72.91	72.68	72.50
F1	72.39	72.07	71.79	71.52	71.25	70.98	70.70	70.39	70.09	69.81	69.59
F2	71.47	71.17	70.87	70.58	70.29	69.99	69.66	seal broke			
F3	71.01	70.68	70.38	70.09	69.81	69.53	69.23	68.91	68.58	68.30	68.07
S1	84.58	84.59	84.58	84.56	84.53	84.50	84.47	84.44	84.41	84.39	84.36
S2	84.32	84.32	84.30	84.26	84.24	84.21	84.17	84.14	84.10	84.07	84.04
S3	86.17	86.19	86.18	86.16	86.14	86.12	86.09	86.06	86.04	86.02	85.98

APPENDIX F: WATER VAPOR TRANSMISSION – ASTM E96-00

WATER VAPOR TRANSMISSION CALCULATIONS

Sample	% weight loss	Average weight loss	Weight change (g)	WVT (g/h·m^2)	Average WVT
A1	1.94	1.99	1.40	0.45	0.45
A2	1.92		1.38	0.44	
A3	2.13		1.45	0.46	
B1	1.83	1.50	1.33	0.43	0.36
B2	1.40		1.05	0.34	
B3	1.28		0.95	0.30	
C1	4.95	4.34	3.49	1.12	0.97
C2	4.51		3.03	0.97	
C3	3.57		2.55	0.82	
D1	3.01	2.91	2.14	0.69	0.68
D2	2.61		1.93	0.62	
D3	3.11		2.30	0.74	
E1	3.09	3.06	2.26	0.72	0.73
E2	2.89		2.18	0.70	
E3	3.20		2.40	0.77	
F1	3.87	3.51	2.80	0.90	0.94
F2	2.53		1.81	0.97	
F3	4.14		2.94	0.94	
S1	0.26	0.27	0.22	0.07	0.07
S2	0.33		0.28	0.09	
S3	0.22		0.19	0.06	

Key to Samples	
Group A	cement/lime putty mortars
Group B	cement/lime putty mortars with acrylic
Group C	feebly hydraulic lime mortars
Group D	feebly hydraulic lime mortars with acrylic
Group E	moderately hydraulic lime mortars
Group F	moderately hydraulic lime mortars with acrylic
Group S	Connecticut brownstone

APPENDIX F: WATER VAPOR TRANSMISSION – ASTM E96-00

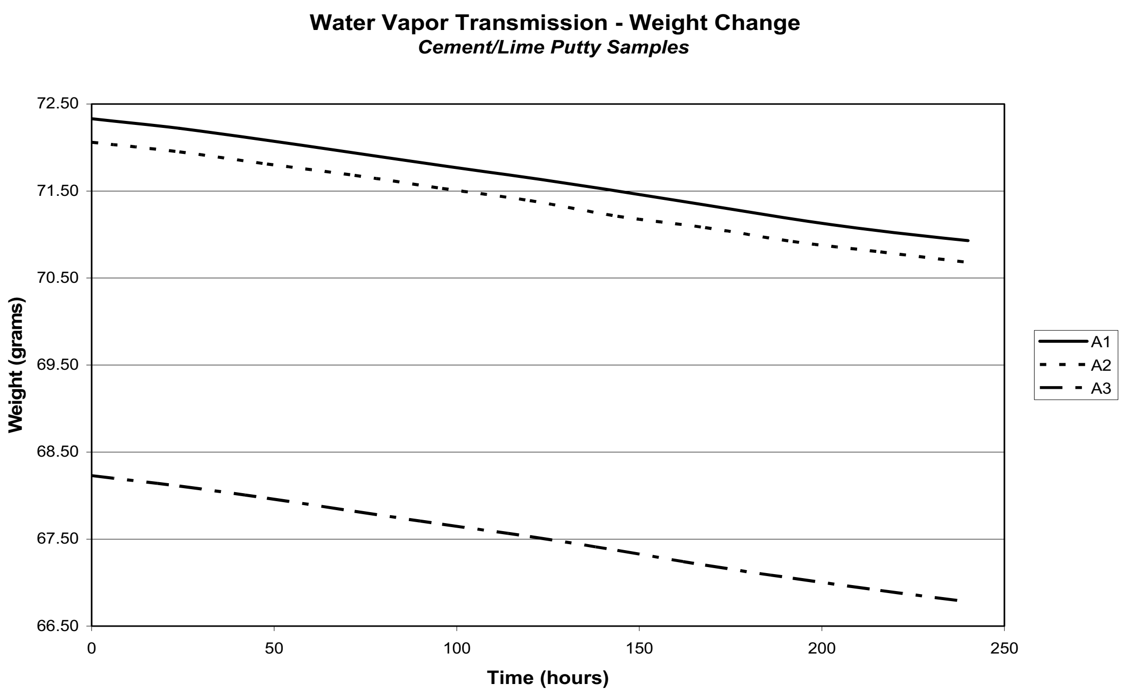
PERMEANCE AND PERMEABILITY CALCULATIONS

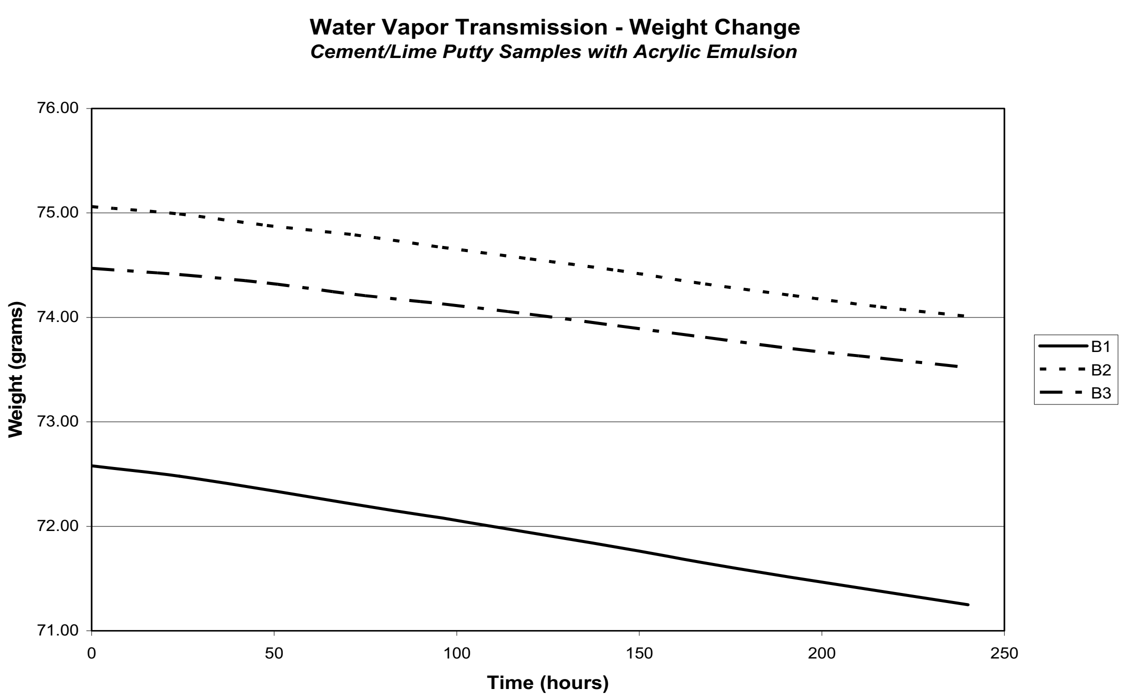
Sample	Time (hours)	S (Pa)	$S(R_1-R_2)$	Permeance ($g/Pa \cdot s \cdot m^2$)	Average Permeance	Permeability (perm·cm)	Average Permeability
A1	240	4.50E+03	2.25E+03	5.55E-08	5.59E-08	7.21E-08	7.26E-08
A2	240	4.50E+03	2.25E+03	5.47E-08		7.11E-08	
A3	240	4.50E+03	2.25E+03	5.74E-08		7.47E-08	
B1	240	4.50E+03	2.25E+03	5.27E-08	4.40E-08	6.85E-08	5.72E-08
B2	240	4.50E+03	2.25E+03	4.16E-08		5.41E-08	
B3	240	4.50E+03	2.25E+03	3.76E-08		4.89E-08	
C1	240	4.50E+03	2.25E+03	1.38E-07	1.20E-07	1.80E-07	1.56E-07
C2	240	4.50E+03	2.25E+03	1.20E-07		1.56E-07	
C3	240	4.50E+03	2.25E+03	1.01E-07		1.31E-07	
D1	240	4.50E+03	2.25E+03	8.48E-08	8.41E-08	1.10E-07	1.09E-07
D2	240	4.50E+03	2.25E+03	7.64E-08		9.94E-08	
D3	240	4.50E+03	2.25E+03	9.11E-08		1.18E-07	
E1	240	4.50E+03	2.25E+03	8.95E-08	9.03E-08	1.16E-07	1.17E-07
E2	240	4.50E+03	2.25E+03	8.64E-08		1.12E-07	
E3	240	4.50E+03	2.25E+03	9.51E-08		1.24E-07	
F1	240	4.50E+03	2.25E+03	1.11E-07	1.16E-07	1.44E-07	1.50E-07
F2	144	4.50E+03	2.25E+03	1.19E-07		1.55E-07	
F3	240	4.50E+03	2.25E+03	1.16E-07		1.51E-07	
S1	240	4.50E+03	2.25E+03	8.71E-09	9.11E-09	1.13E-08	1.18E-08
S2	240	4.50E+03	2.25E+03	1.11E-08		1.44E-08	
S3	240	4.50E+03	2.25E+03	7.53E-09		9.78E-09	

Key to Samples	
Group A	cement/lime putty mortars
Group B	cement/lime putty mortars with acrylic
Group C	feebly hydraulic lime mortars
Group D	feebly hydraulic lime mortars with acrylic
Group E	moderately hydraulic lime mortars
Group F	moderately hydraulic lime mortars with acrylic
Group S	Connecticut brownstone

APPENDIX F: WATER VAPOR TRANSMISSION – ASTM E96-00

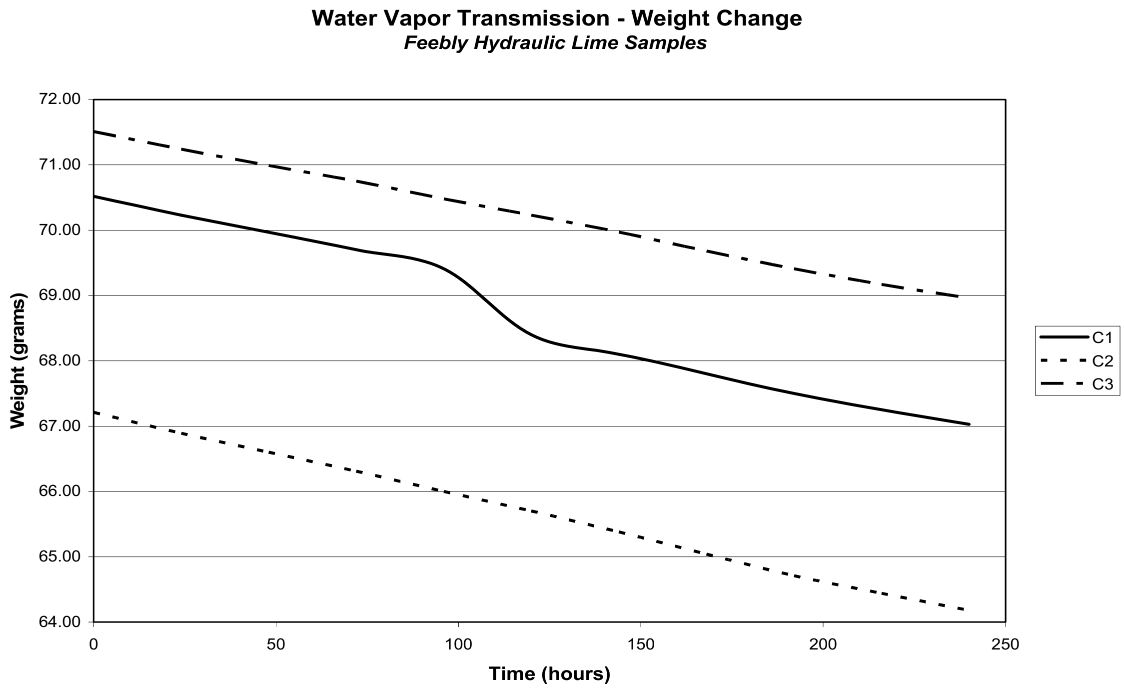
WATER VAPOR TRANSMISSION GRAPHS

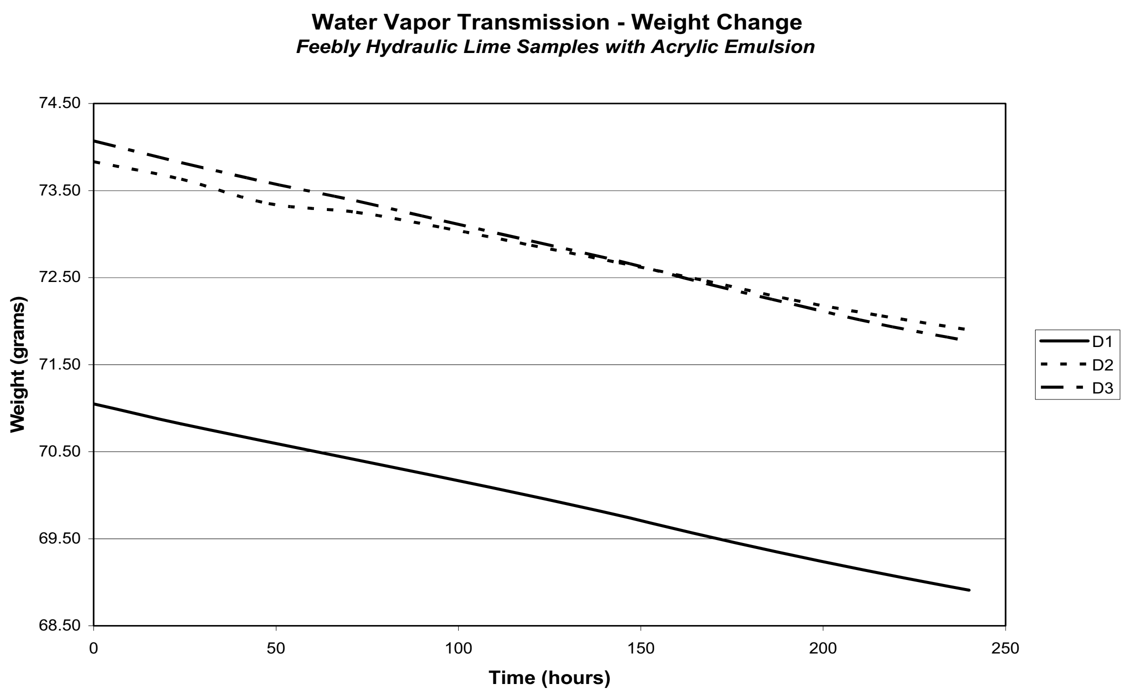




Appendix F: Water Vapor Transmission – ASTM E96-00

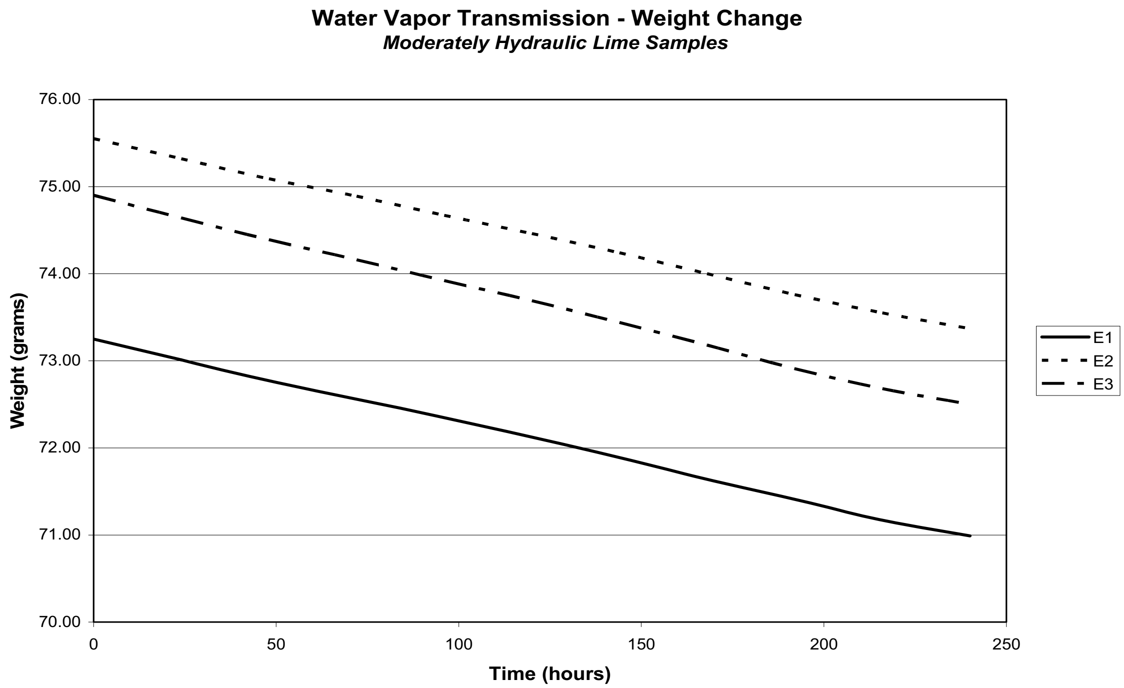
Water Vapor Transmission Graphs

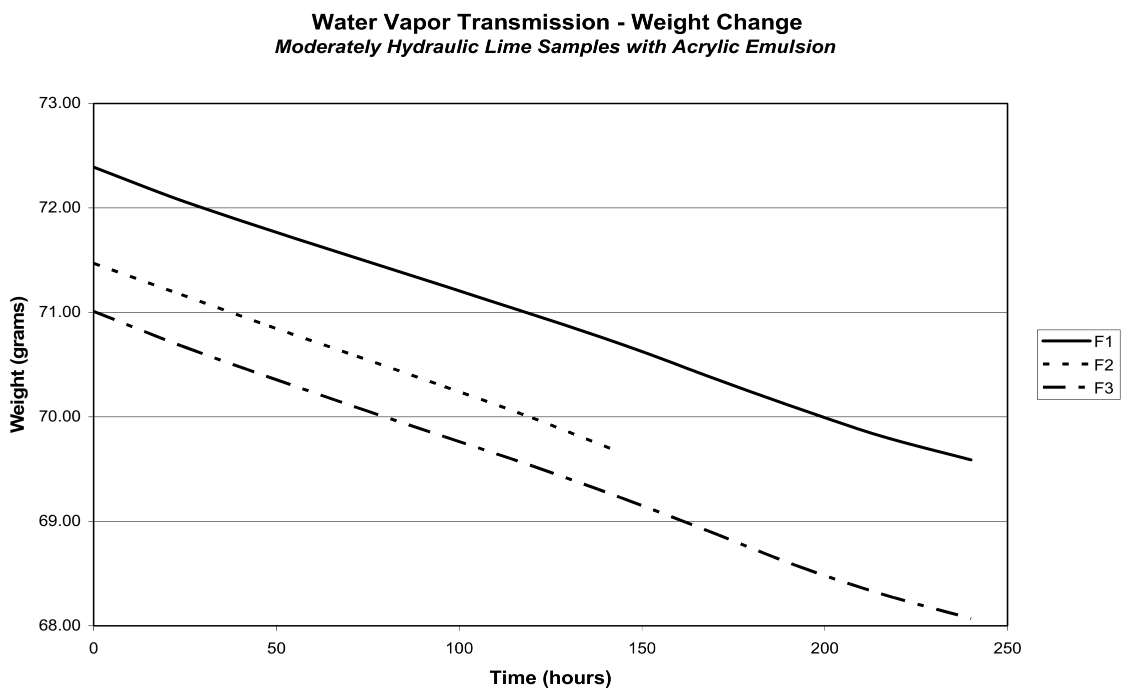




APPENDIX F: WATER VAPOR TRANSMISSION – ASTM E96-00

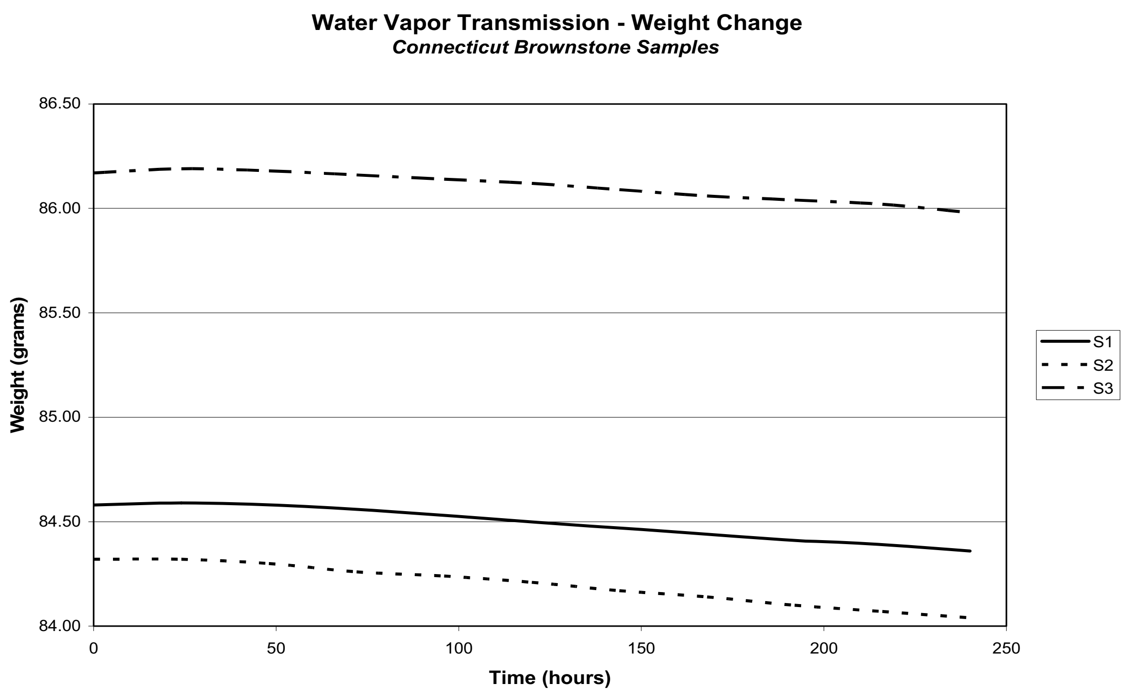
WATER VAPOR TRANSMISSION GRAPHS





APPENDIX F: WATER VAPOR TRANSMISSION – ASTM E96-00

WATER VAPOR TRANSMISSION GRAPHS



APPENDIX G: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION MEASUREMENTS FOR SAMPLE A1

Time (hours)	Weight (g)	Difference in successive weighings (g)	Change in weight from initial weight (g)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	236.87	0.00	0.00	0.00	0.00
0.08	257.13	20.26	20.26	8.55	4.28
0.17	258.41	1.28	21.54	9.09	8.82
0.25	259.07	0.66	22.20	9.37	9.23
0.33	259.71	0.64	22.84	9.64	9.51
0.42	260.09	0.38	23.22	9.80	9.72
0.50	260.35	0.26	23.48	9.91	9.86
0.58	260.48	0.13	23.61	9.97	9.94
0.67	260.48	0.00	23.61	9.97	9.97
0.75	260.60	0.12	23.73	10.02	9.99
0.83	260.70	0.10	23.83	10.06	10.04
0.92	260.68	-0.02	23.81	10.05	10.06
1.00	260.84	0.16	23.97	10.12	10.09
1.25	260.80	-0.04	23.93	10.10	10.11
1.50	260.76	-0.04	23.89	10.09	10.09
1.75	260.91	0.15	24.04	10.15	10.12
2.00	260.78	-0.13	23.91	10.09	10.12
2.25	261.02	0.24	24.15	10.20	10.14
2.50	260.94	-0.08	24.07	10.16	10.18
2.75	260.97	0.03	24.10	10.17	10.17
3.00	261.12	0.15	24.25	10.24	10.21
4.00	261.25	0.13	24.38	10.29	10.27
5.00	261.28	0.03	24.41	10.31	10.30
6.00	261.32	0.04	24.45	10.32	10.31
7.00	261.40	0.08	24.53	10.36	10.34
8.00	261.58	0.18	24.71	10.43	10.39
24.0	262.16	0.58	25.29	10.68	10.55
48.0	262.43	0.27	25.56	10.79	10.73
72.0	262.47	0.04	25.60	10.81	10.80
96.0	262.52	0.05	25.65	10.83	10.82

APPENDIX G: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION MEASUREMENTS FOR SAMPLE A2

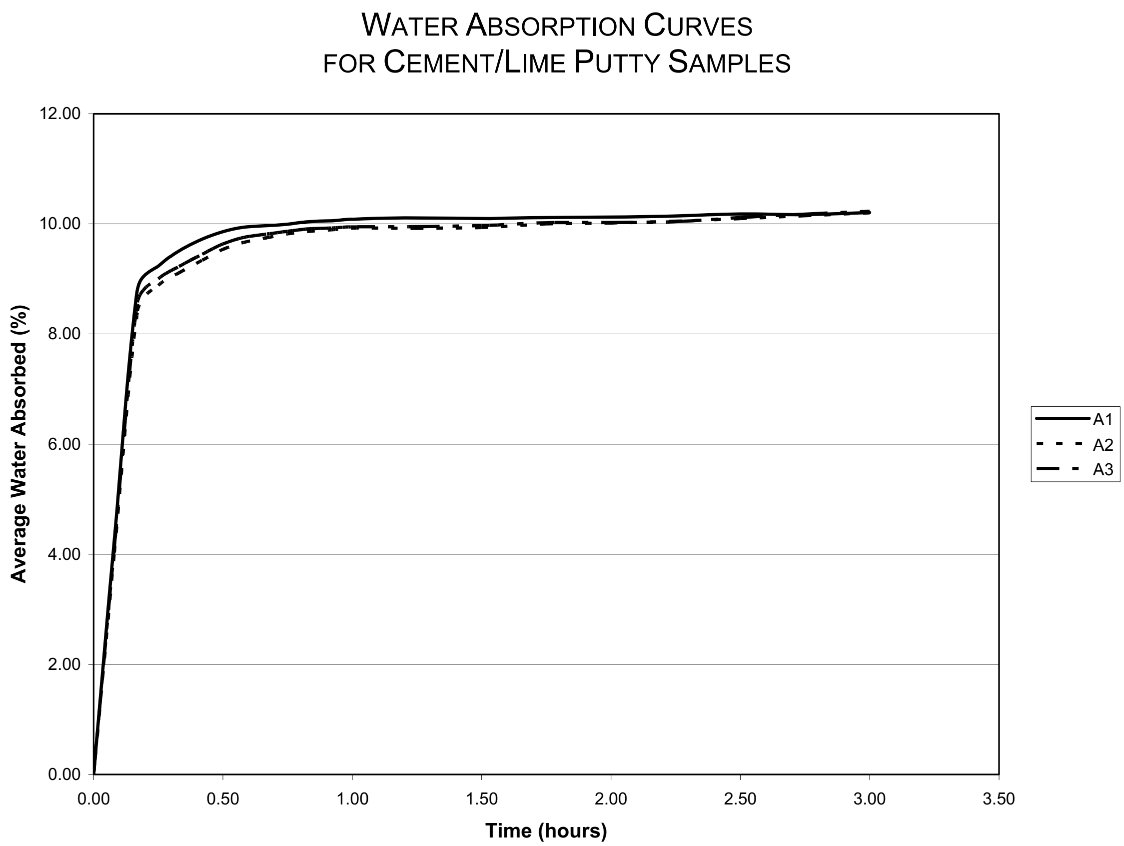
Time (hours)	Weight (g)	Difference in successive weighings (g)	Change in weight from initial weight (g)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	243.60	0.00	0.00	0.00	0.00
0.08	263.25	19.65	19.65	8.07	4.03
0.17	264.97	1.72	21.37	8.77	8.42
0.25	265.51	0.54	21.91	8.99	8.88
0.33	266.08	0.57	22.48	9.23	9.11
0.42	266.63	0.55	23.03	9.45	9.34
0.50	267.04	0.41	23.44	9.62	9.54
0.58	267.24	0.20	23.64	9.70	9.66
0.67	267.46	0.22	23.86	9.79	9.75
0.75	267.58	0.12	23.98	9.84	9.82
0.83	267.67	0.09	24.07	9.88	9.86
0.92	267.73	0.06	24.13	9.91	9.89
1.00	267.83	0.10	24.23	9.95	9.93
1.25	267.70	-0.13	24.10	9.89	9.92
1.50	267.90	0.20	24.30	9.98	9.93
1.75	268.02	0.12	24.42	10.02	10.00
2.00	267.98	-0.04	24.38	10.01	10.02
2.25	268.18	0.20	24.58	10.09	10.05
2.50	268.21	0.03	24.61	10.10	10.10
2.75	268.43	0.22	24.83	10.19	10.15
3.00	268.46	0.03	24.86	10.21	10.20
4.00	268.40	-0.06	24.80	10.18	10.19
5.00	268.49	0.09	24.89	10.22	10.20
6.00	268.03	-0.46	24.43	10.03	10.12
7.00	268.35	0.32	24.75	10.16	10.09
8.00	268.48	0.13	24.88	10.21	10.19
24.0	269.26	0.78	25.66	10.53	10.37
48.0	269.56	0.30	25.96	10.66	10.60
72.0	269.50	-0.06	25.90	10.63	10.64
96.0	269.62	0.12	26.02	10.68	10.66

APPENDIX G: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION MEASUREMENTS FOR SAMPLE A3

Time (hours)	Weight (g)	Difference in successive weighings (g)	Change in weight from initial weight (g)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	237.48	0.00	0.00	0.00	0.00
0.08	257.12	19.64	19.64	8.27	4.14
0.17	258.57	1.45	21.09	8.88	8.58
0.25	259.14	0.57	21.66	9.12	9.00
0.33	259.64	0.50	22.16	9.33	9.23
0.42	260.20	0.56	22.72	9.57	9.45
0.50	260.52	0.32	23.04	9.70	9.63
0.58	260.76	0.24	23.28	9.80	9.75
0.67	260.82	0.06	23.34	9.83	9.82
0.75	260.99	0.17	23.51	9.90	9.86
0.83	261.03	0.04	23.55	9.92	9.91
0.92	261.07	0.04	23.59	9.93	9.93
1.00	261.13	0.06	23.65	9.96	9.95
1.25	261.09	-0.04	23.61	9.94	9.95
1.50	261.22	0.13	23.74	10.00	9.97
1.75	261.34	0.12	23.86	10.05	10.02
2.00	261.24	-0.10	23.76	10.01	10.03
2.25	261.41	0.17	23.93	10.08	10.04
2.50	261.59	0.18	24.11	10.15	10.11
2.75	261.71	0.12	24.23	10.20	10.18
3.00	261.83	0.12	24.35	10.25	10.23
4.00	261.71	-0.12	24.23	10.20	10.23
5.00	261.80	0.09	24.32	10.24	10.22
6.00	261.89	0.09	24.41	10.28	10.26
7.00	262.01	0.12	24.53	10.33	10.30
8.00	261.96	-0.05	24.48	10.31	10.32
24.0	263.04	1.08	25.56	10.76	10.54
48.0	263.50	0.46	26.02	10.96	10.86
72.0	263.47	-0.03	25.99	10.94	10.95
96.0	263.39	-0.08	25.91	10.91	10.93

APPENDIX G: WATER ABSORPTION – NORMAL 7/81



APPENDIX G: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION MEASUREMENTS FOR SAMPLE B1

Time (hours)	Weight (g)	Difference in successive weighings (g)	Change in weight from initial weight (g)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	252.19	0.00	0.00	0.00	0.00
0.08	268.81	16.62	16.62	6.59	3.30
0.17	270.28	1.47	18.09	7.17	6.88
0.25	271.01	0.73	18.82	7.46	7.32
0.33	271.50	0.49	19.31	7.66	7.56
0.42	272.03	0.53	19.84	7.87	7.76
0.50	272.34	0.31	20.15	7.99	7.93
0.58	272.67	0.33	20.48	8.12	8.06
0.67	272.82	0.15	20.63	8.18	8.15
0.75	272.94	0.12	20.75	8.23	8.20
0.83	273.04	0.10	20.85	8.27	8.25
0.92	273.14	0.10	20.95	8.31	8.29
1.00	273.28	0.14	21.09	8.36	8.33
1.25	273.27	-0.01	21.08	8.36	8.36
1.50	273.33	0.06	21.14	8.38	8.37
1.75	273.43	0.10	21.24	8.42	8.40
2.00	273.52	0.09	21.33	8.46	8.44
2.25	273.52	0.00	21.33	8.46	8.46
2.50	273.55	0.03	21.36	8.47	8.46
2.75	273.60	0.05	21.41	8.49	8.48
3.00	273.69	0.09	21.50	8.53	8.51
4.00	273.69	0.00	21.50	8.53	8.53
5.00	273.84	0.15	21.65	8.58	8.56
6.00	273.90	0.06	21.71	8.61	8.60
7.00	274.01	0.11	21.82	8.65	8.63
8.00	274.08	0.07	21.89	8.68	8.67
24.0	274.18	0.10	21.99	8.72	8.70
48.0	274.83	0.65	22.64	8.98	8.85
72.0	274.78	-0.05	22.59	8.96	8.97
96.0	274.78	0.00	22.59	8.96	8.96

APPENDIX G: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION MEASUREMENTS FOR SAMPLE B2

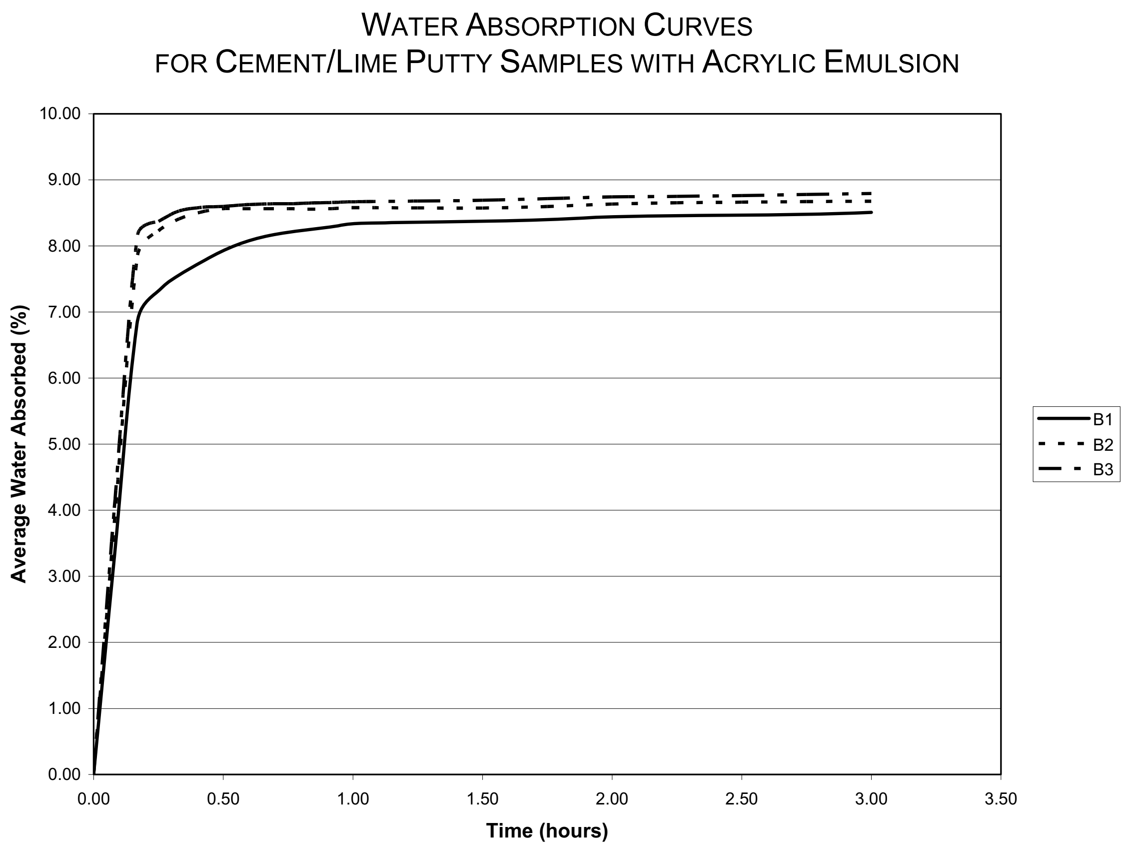
Time (hours)	Weight (g)	Difference in successive weighings (g)	Change in weight from initial weight (g)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	247.01	0.00	0.00	0.00	0.00
0.08	265.82	18.81	18.81	7.62	3.81
0.17	267.04	1.22	20.03	8.11	7.86
0.25	267.62	0.58	20.61	8.34	8.23
0.33	267.94	0.32	20.93	8.47	8.41
0.42	268.15	0.21	21.14	8.56	8.52
0.50	268.18	0.03	21.17	8.57	8.56
0.58	268.15	-0.03	21.14	8.56	8.56
0.67	268.18	0.03	21.17	8.57	8.56
0.75	268.15	-0.03	21.14	8.56	8.56
0.83	268.14	-0.01	21.13	8.55	8.56
0.92	268.19	0.05	21.18	8.57	8.56
1.00	268.21	0.02	21.20	8.58	8.58
1.25	268.17	-0.04	21.16	8.57	8.57
1.50	268.20	0.03	21.19	8.58	8.57
1.75	268.29	0.09	21.28	8.62	8.60
2.00	268.38	0.09	21.37	8.65	8.63
2.25	268.39	0.01	21.38	8.66	8.65
2.50	268.42	0.03	21.41	8.67	8.66
2.75	268.44	0.02	21.43	8.68	8.67
3.00	268.44	0.00	21.43	8.68	8.68
4.00	268.49	0.05	21.48	8.70	8.69
5.00	268.71	0.22	21.70	8.79	8.74
6.00	268.60	-0.11	21.59	8.74	8.76
7.00	268.86	0.26	21.85	8.85	8.79
8.00	268.88	0.02	21.87	8.85	8.85
24.0	269.15	0.27	22.14	8.96	8.91
48.0	269.82	0.67	22.81	9.23	9.10
72.0	269.78	-0.04	22.77	9.22	9.23
96.0	269.60	-0.18	22.59	9.15	9.18

APPENDIX G: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION MEASUREMENTS FOR SAMPLE B3

Time (hours)	Weight (g)	Difference in successive weighings (g)	Change in weight from initial weight (g)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	250.82	0.00	0.00	0.00	0.00
0.08	271.06	20.24	20.24	8.07	4.03
0.17	271.56	0.50	20.74	8.27	8.17
0.25	272.07	0.51	21.25	8.47	8.37
0.33	272.35	0.28	21.53	8.58	8.53
0.42	272.36	0.01	21.54	8.59	8.59
0.50	272.41	0.05	21.59	8.61	8.60
0.58	272.48	0.07	21.66	8.64	8.62
0.67	272.48	0.00	21.66	8.64	8.64
0.75	272.49	0.01	21.67	8.64	8.64
0.83	272.53	0.04	21.71	8.66	8.65
0.92	272.54	0.01	21.72	8.66	8.66
1.00	272.58	0.04	21.76	8.68	8.67
1.25	272.60	0.02	21.78	8.68	8.68
1.50	272.64	0.04	21.82	8.70	8.69
1.75	272.72	0.08	21.90	8.73	8.72
2.00	272.77	0.05	21.95	8.75	8.74
2.25	272.76	-0.01	21.94	8.75	8.75
2.50	272.83	0.07	22.01	8.78	8.76
2.75	272.85	0.02	22.03	8.78	8.78
3.00	272.90	0.05	22.08	8.80	8.79
4.00	272.98	0.08	22.16	8.84	8.82
5.00	273.10	0.12	22.28	8.88	8.86
6.00	273.15	0.05	22.33	8.90	8.89
7.00	273.27	0.12	22.45	8.95	8.93
8.00	273.32	0.05	22.50	8.97	8.96
24.0	273.68	0.36	22.86	9.11	9.04
48.0	274.30	0.62	23.48	9.36	9.24
72.0	274.20	-0.10	23.38	9.32	9.34
96.0	274.20	0.00	23.38	9.32	9.32

APPENDIX G: WATER ABSORPTION – NORMAL 7/81



APPENDIX G: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION MEASUREMENTS FOR SAMPLE C1

Time (hours)	Weight (g)	Difference in successive weighings (g)	Change in weight from initial weight (g)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	251.06	0.00	0.00	0.00	0.00
0.08	276.96	25.90	25.90	10.32	5.16
0.17	276.86	-0.10	25.80	10.28	10.30
0.25	276.84	-0.02	25.78	10.27	10.27
0.33	276.90	0.06	25.84	10.29	10.28
0.42	276.87	-0.03	25.81	10.28	10.29
0.50	276.88	0.01	25.82	10.28	10.28
0.58	276.96	0.08	25.90	10.32	10.30
0.67	276.89	-0.07	25.83	10.29	10.30
0.75	276.87	-0.02	25.81	10.28	10.28
0.83	276.90	0.03	25.84	10.29	10.29
0.92	276.92	0.02	25.86	10.30	10.30
1.00	276.96	0.04	25.90	10.32	10.31
1.25	276.97	0.01	25.91	10.32	10.32
1.50	276.98	0.01	25.92	10.32	10.32
1.75	276.94	-0.04	25.88	10.31	10.32
2.00	277.02	0.08	25.96	10.34	10.32
2.25	277.07	0.05	26.01	10.36	10.35
2.50	277.10	0.03	26.04	10.37	10.37
2.75	277.15	0.05	26.09	10.39	10.38
3.00	277.12	-0.03	26.06	10.38	10.39
4.00	277.24	0.12	26.18	10.43	10.40
5.00	277.37	0.13	26.31	10.48	10.45
6.00	277.39	0.02	26.33	10.49	10.48
7.00	277.49	0.10	26.43	10.53	10.51
8.00	277.44	-0.05	26.38	10.51	10.52
24.0	277.55	0.11	26.49	10.55	10.53
48.0	277.88	0.33	26.82	10.68	10.62
72.0	277.78	-0.10	26.72	10.64	10.66
96.0	277.90	0.12	26.84	10.69	10.67

APPENDIX G: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION MEASUREMENTS FOR SAMPLE C2

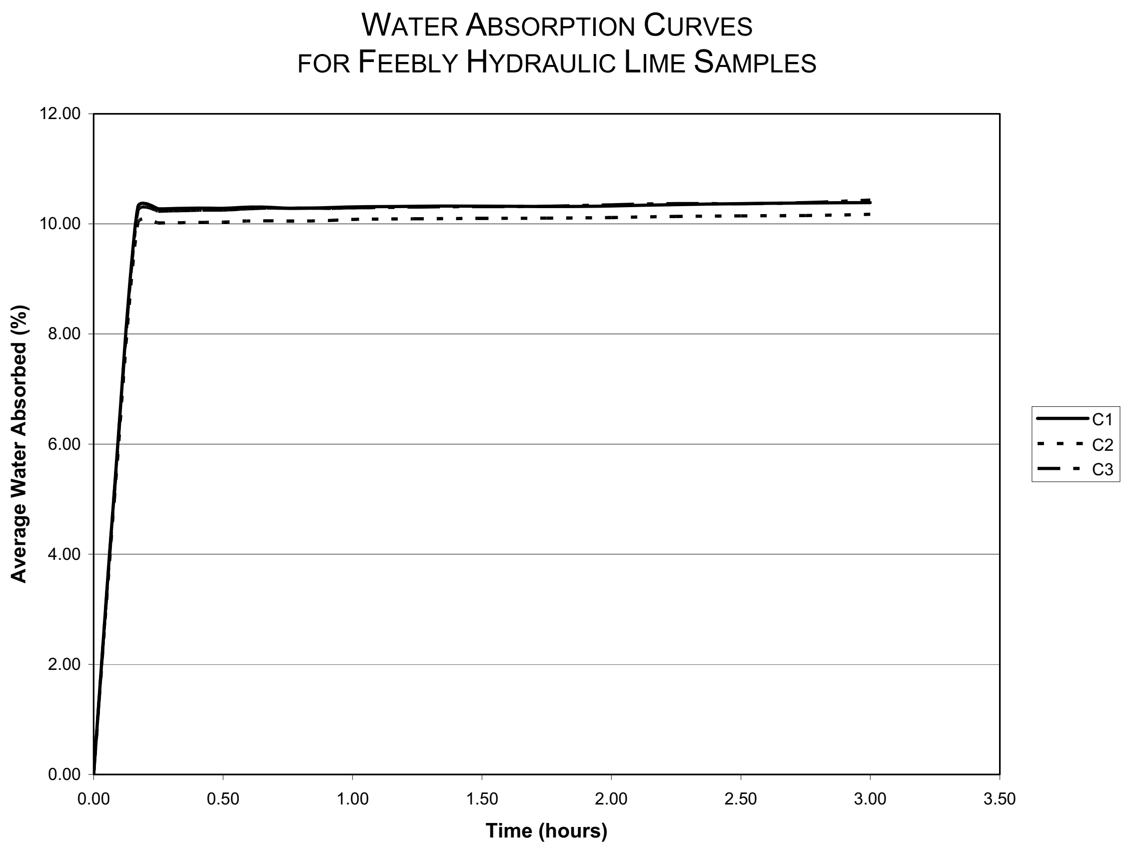
Time (hours)	Weight (g)	Difference in successive weighings (g)	Change in weight from initial weight (g)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	260.69	0.00	0.00	0.00	0.00
0.08	286.74	26.05	26.05	9.99	5.00
0.17	286.81	0.07	26.12	10.02	10.01
0.25	286.79	-0.02	26.10	10.01	10.02
0.33	286.84	0.05	26.15	10.03	10.02
0.42	286.82	-0.02	26.13	10.02	10.03
0.50	286.87	0.05	26.18	10.04	10.03
0.58	286.91	0.04	26.22	10.06	10.05
0.67	286.90	-0.01	26.21	10.05	10.06
0.75	286.88	-0.02	26.19	10.05	10.05
0.83	286.91	0.03	26.22	10.06	10.05
0.92	286.94	0.03	26.25	10.07	10.06
1.00	287.00	0.06	26.31	10.09	10.08
1.25	287.00	0.00	26.31	10.09	10.09
1.50	287.04	0.04	26.35	10.11	10.10
1.75	287.02	-0.02	26.33	10.10	10.10
2.00	287.10	0.08	26.41	10.13	10.12
2.25	287.12	0.02	26.43	10.14	10.13
2.50	287.16	0.04	26.47	10.15	10.15
2.75	287.15	-0.01	26.46	10.15	10.15
3.00	287.27	0.12	26.58	10.20	10.17
4.00	287.34	0.07	26.65	10.22	10.21
5.00	287.37	0.03	26.68	10.23	10.23
6.00	287.46	0.09	26.77	10.27	10.25
7.00	287.42	-0.04	26.73	10.25	10.26
8.00	287.46	0.04	26.77	10.27	10.26
24.0	287.69	0.23	27.00	10.36	10.31
48.0	288.08	0.39	27.39	10.51	10.43
72.0	287.94	-0.14	27.25	10.45	10.48
96.0	288.03	0.09	27.34	10.49	10.47

APPENDIX G: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION MEASUREMENTS FOR SAMPLE C3

Time (hours)	Weight (g)	Difference in successive weighings (g)	Change in weight from initial weight (g)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	250.90	0.00	0.00	0.00	0.00
0.08	276.53	25.63	25.63	10.22	5.11
0.17	276.57	0.04	25.67	10.23	10.22
0.25	276.57	0.00	25.67	10.23	10.23
0.33	276.61	0.04	25.71	10.25	10.24
0.42	276.62	0.01	25.72	10.25	10.25
0.50	276.62	0.00	25.72	10.25	10.25
0.58	276.72	0.10	25.82	10.29	10.27
0.67	276.70	-0.02	25.80	10.28	10.29
0.75	276.71	0.01	25.81	10.29	10.28
0.83	276.71	0.00	25.81	10.29	10.29
0.92	276.69	-0.02	25.79	10.28	10.28
1.00	276.75	0.06	25.85	10.30	10.29
1.25	276.77	0.02	25.87	10.31	10.31
1.50	276.79	0.02	25.89	10.32	10.31
1.75	276.79	0.00	25.89	10.32	10.32
2.00	276.93	0.14	26.03	10.37	10.35
2.25	276.90	-0.03	26.00	10.36	10.37
2.50	276.92	0.02	26.02	10.37	10.37
2.75	276.99	0.07	26.09	10.40	10.38
3.00	277.15	0.16	26.25	10.46	10.43
4.00	277.22	0.07	26.32	10.49	10.48
5.00	277.32	0.10	26.42	10.53	10.51
6.00	277.33	0.01	26.43	10.53	10.53
7.00	277.30	-0.03	26.40	10.52	10.53
8.00	277.37	0.07	26.47	10.55	10.54
24.0	277.62	0.25	26.72	10.65	10.60
48.0	278.03	0.41	27.13	10.81	10.73
72.0	277.87	-0.16	26.97	10.75	10.78
96.0	277.95	0.08	27.05	10.78	10.77

APPENDIX G: WATER ABSORPTION – NORMAL 7/81



APPENDIX G: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION MEASUREMENTS FOR SAMPLE D1

Time (hours)	Weight (g)	Difference in successive weighings (g)	Change in weight from initial weight (g)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	227.29	0.00	0.00	0.00	0.00
0.08	255.57	28.28	28.28	12.44	6.22
0.17	255.55	-0.02	28.26	12.43	12.44
0.25	255.64	0.09	28.35	12.47	12.45
0.33	255.48	-0.16	28.19	12.40	12.44
0.42	255.56	0.08	28.27	12.44	12.42
0.50	255.61	0.05	28.32	12.46	12.45
0.58	255.49	-0.12	28.20	12.41	12.43
0.67	255.46	-0.03	28.17	12.39	12.40
0.75	255.59	0.13	28.30	12.45	12.42
0.83	255.73	0.14	28.44	12.51	12.48
0.92	255.73	0.00	28.44	12.51	12.51
1.00	255.70	-0.03	28.41	12.50	12.51
1.25	255.64	-0.06	28.35	12.47	12.49
1.50	255.68	0.04	28.39	12.49	12.48
1.75	255.74	0.06	28.45	12.52	12.50
2.00	255.78	0.04	28.49	12.53	12.53
2.25	255.66	-0.12	28.37	12.48	12.51
2.50	255.46	-0.20	28.17	12.39	12.44
2.75	255.26	-0.20	27.97	12.31	12.35
3.00	255.07	-0.19	27.78	12.22	12.26
4.00	255.62	0.55	28.33	12.46	12.34
5.00	255.64	0.02	28.35	12.47	12.47
6.00	255.31	-0.33	28.02	12.33	12.40
7.00	255.62	0.31	28.33	12.46	12.40
8.00	255.65	0.03	28.36	12.48	12.47
24.0	255.59	-0.06	28.30	12.45	12.46
48.0	255.97	0.38	28.68	12.62	12.53
72.0	255.68	-0.29	28.39	12.49	12.55
96.0	255.76	0.08	28.47	12.53	12.51

APPENDIX G: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION MEASUREMENTS FOR SAMPLE D2

Time (hours)	Weight (g)	Difference in successive weighings (g)	Change in weight from initial weight (g)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	231.74	0.00	0.00	0.00	0.00
0.08	260.79	29.05	29.05	12.54	6.27
0.17	261.18	0.39	29.44	12.70	12.62
0.25	261.04	-0.14	29.30	12.64	12.67
0.33	260.94	-0.10	29.20	12.60	12.62
0.42	261.05	0.11	29.31	12.65	12.62
0.50	260.94	-0.11	29.20	12.60	12.62
0.58	261.11	0.17	29.37	12.67	12.64
0.67	261.05	-0.06	29.31	12.65	12.66
0.75	261.02	-0.03	29.28	12.63	12.64
0.83	261.08	0.06	29.34	12.66	12.65
0.92	261.19	0.11	29.45	12.71	12.68
1.00	261.17	-0.02	29.43	12.70	12.70
1.25	261.06	-0.11	29.32	12.65	12.68
1.50	261.52	0.46	29.78	12.85	12.75
1.75	261.25	-0.27	29.51	12.73	12.79
2.00	261.45	0.20	29.71	12.82	12.78
2.25	261.74	0.29	30.00	12.95	12.88
2.50	261.21	-0.53	29.47	12.72	12.83
2.75	260.93	-0.28	29.19	12.60	12.66
3.00	260.96	0.03	29.22	12.61	12.60
4.00	261.22	0.26	29.48	12.72	12.67
5.00	271.17	9.95	39.43	17.01	14.87
6.00	260.93	-10.24	29.19	12.60	14.81
7.00	261.33	0.40	29.59	12.77	12.68
8.00	261.10	-0.23	29.36	12.67	12.72
24.0	261.05	-0.05	29.31	12.65	12.66
48.0	261.56	0.51	29.82	12.87	12.76
72.0	261.25	-0.31	29.51	12.73	12.80
96.0	261.34	0.09	29.60	12.77	12.75

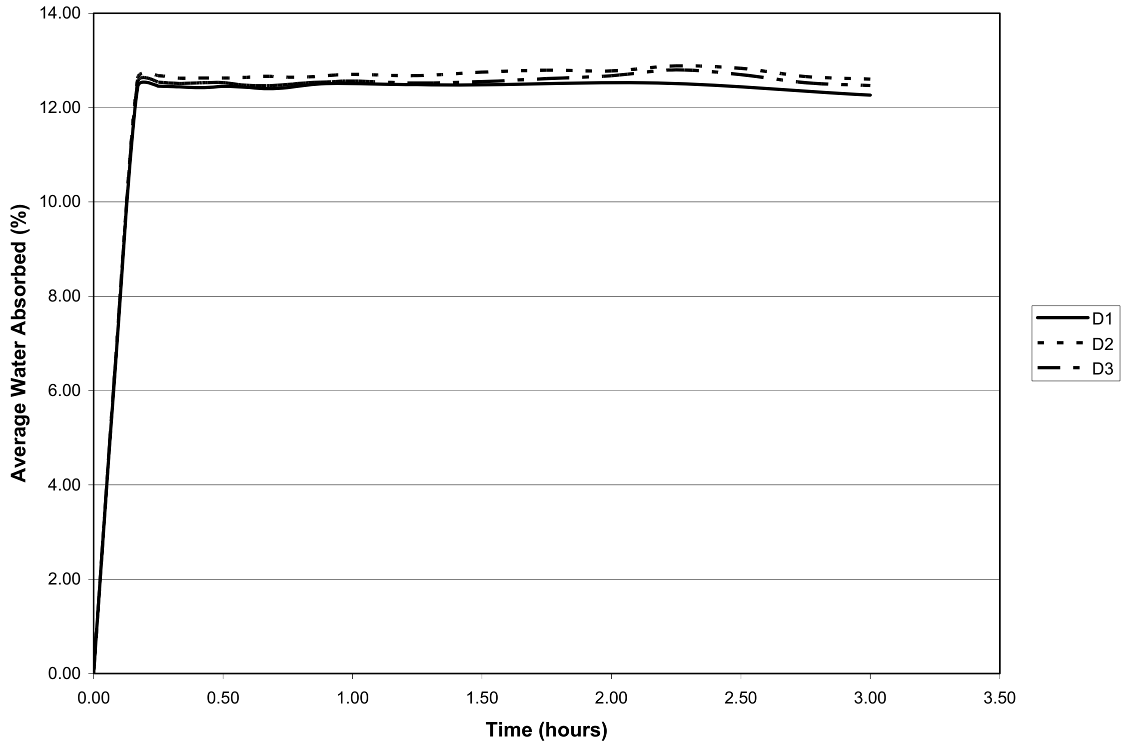
APPENDIX G: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION MEASUREMENTS FOR SAMPLE D3

Time (hours)	Weight (g)	Difference in successive weighings (g)	Change in weight from initial weight (g)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	230.00	0.00	0.00	0.00	0.00
0.08	258.84	28.84	28.84	12.54	6.27
0.17	258.85	0.01	28.85	12.54	12.54
0.25	258.82	-0.03	28.82	12.53	12.54
0.33	258.73	-0.09	28.73	12.49	12.51
0.42	258.89	0.16	28.89	12.56	12.53
0.50	258.74	-0.15	28.74	12.50	12.53
0.58	258.65	-0.09	28.65	12.46	12.48
0.67	258.67	0.02	28.67	12.47	12.46
0.75	258.78	0.11	28.78	12.51	12.49
0.83	258.84	0.06	28.84	12.54	12.53
0.92	258.87	0.03	28.87	12.55	12.55
1.00	258.92	0.05	28.92	12.57	12.56
1.25	258.67	-0.25	28.67	12.47	12.52
1.50	259.06	0.39	29.06	12.63	12.55
1.75	258.96	-0.10	28.96	12.59	12.61
2.00	259.34	0.38	29.34	12.76	12.67
2.25	259.53	0.19	29.53	12.84	12.80
2.50	258.88	-0.65	28.88	12.56	12.70
2.75	258.74	-0.14	28.74	12.50	12.53
3.00	258.60	-0.14	28.60	12.43	12.47
4.00	258.94	0.34	28.94	12.58	12.51
5.00	258.99	0.05	28.99	12.60	12.59
6.00	258.75	-0.24	28.75	12.50	12.55
7.00	259.02	0.27	29.02	12.62	12.56
8.00	258.77	-0.25	28.77	12.51	12.56
24.0	258.82	0.05	28.82	12.53	12.52
48.0	259.09	0.27	29.09	12.65	12.59
72.0	258.98	-0.11	28.98	12.60	12.62
96.0	259.03	0.05	29.03	12.62	12.61

APPENDIX G: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION CURVES
FOR FEEBLY HYDRAULIC LIME SAMPLES WITH ACRYLIC EMULSION



APPENDIX G: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION MEASUREMENTS FOR SAMPLE E1

Time (hours)	Weight (g)	Difference in successive weighings (g)	Change in weight from initial weight (g)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	219.12	0.00	0.00	0.00	0.00
0.08	250.12	31.00	31.00	14.15	7.07
0.17	249.79	-0.33	30.67	14.00	14.07
0.25	249.85	0.06	30.73	14.02	14.01
0.33	249.86	0.01	30.74	14.03	14.03
0.42	249.70	-0.16	30.58	13.96	13.99
0.50	249.63	-0.07	30.51	13.92	13.94
0.58	249.45	-0.18	30.33	13.84	13.88
0.67	249.51	0.06	30.39	13.87	13.86
0.75	250.00	0.49	30.88	14.09	13.98
0.83	249.70	-0.30	30.58	13.96	14.02
0.92	249.39	-0.31	30.27	13.81	13.89
1.00	249.43	0.04	30.31	13.83	13.82
1.25	249.26	-0.17	30.14	13.76	13.79
1.50	249.47	0.21	30.35	13.85	13.80
1.75	249.27	-0.20	30.15	13.76	13.81
2.00	249.27	0.00	30.15	13.76	13.76
2.25	249.14	-0.13	30.02	13.70	13.73
2.50	248.98	-0.16	29.86	13.63	13.66
2.75	249.07	0.09	29.95	13.67	13.65
3.00	249.32	0.25	30.20	13.78	13.73
4.00	249.26	-0.06	30.14	13.76	13.77
5.00	249.47	0.21	30.35	13.85	13.80
6.00	249.16	-0.31	30.04	13.71	13.78
7.00	249.65	0.49	30.53	13.93	13.82
8.00	249.62	-0.03	30.50	13.92	13.93
24.0	249.28	-0.34	30.16	13.76	13.84
48.0	249.40	0.12	30.28	13.82	13.79
72.0	249.23	-0.17	30.11	13.74	13.78
96.0	249.39	0.16	30.27	13.81	13.78

APPENDIX G: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION MEASUREMENTS FOR SAMPLE E2

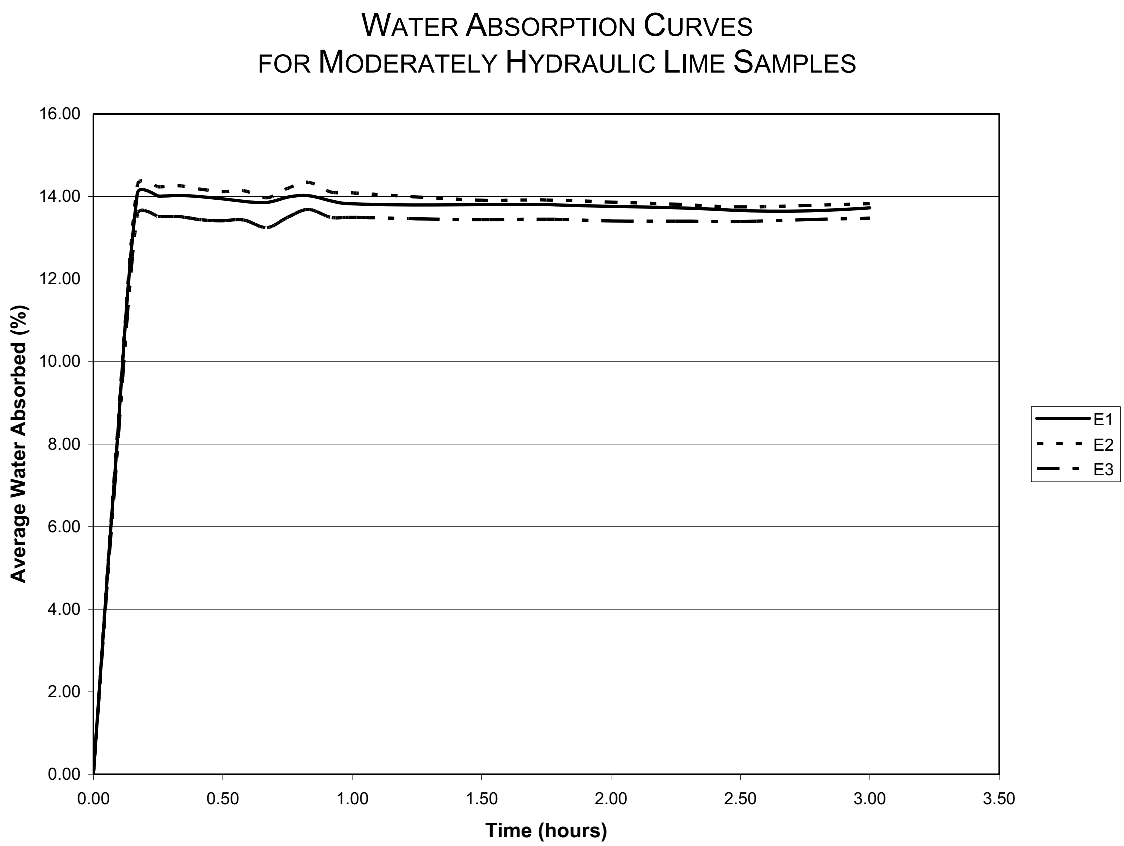
Time (hours)	Weight (g)	Difference in successive weighings (g)	Change in weight from initial weight (g)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	216.65	0.00	0.00	0.00	0.00
0.08	247.70	31.05	31.05	14.33	7.17
0.17	247.48	-0.22	30.83	14.23	14.28
0.25	247.49	0.01	30.84	14.23	14.23
0.33	247.60	0.11	30.95	14.29	14.26
0.42	247.10	-0.50	30.45	14.05	14.17
0.50	247.37	0.27	30.72	14.18	14.12
0.58	247.20	-0.17	30.55	14.10	14.14
0.67	246.63	-0.57	29.98	13.84	13.97
0.75	248.18	1.55	31.53	14.55	14.20
0.83	247.28	-0.90	30.63	14.14	14.35
0.92	247.12	-0.16	30.47	14.06	14.10
1.00	247.22	0.10	30.57	14.11	14.09
1.25	246.70	-0.52	30.05	13.87	13.99
1.50	246.87	0.17	30.22	13.95	13.91
1.75	246.73	-0.14	30.08	13.88	13.92
2.00	246.64	-0.09	29.99	13.84	13.86
2.25	246.51	-0.13	29.86	13.78	13.81
2.50	246.35	-0.16	29.70	13.71	13.75
2.75	246.66	0.31	30.01	13.85	13.78
3.00	246.55	-0.11	29.90	13.80	13.83
4.00	246.46	-0.09	29.81	13.76	13.78
5.00	246.27	-0.19	29.62	13.67	13.72
6.00	246.37	0.10	29.72	13.72	13.69
7.00	246.29	-0.08	29.64	13.68	13.70
8.00	246.66	0.37	30.01	13.85	13.77
24.0	246.50	-0.16	29.85	13.78	13.81
48.0	246.42	-0.08	29.77	13.74	13.76
72.0	246.24	-0.18	29.59	13.66	13.70
96.0	246.09	-0.15	29.44	13.59	13.62

APPENDIX G: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION MEASUREMENTS FOR SAMPLE E3

Time (hours)	Weight (g)	Difference in successive weighings (g)	Change in weight from initial weight (g)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	222.61	0.00	0.00	0.00	0.00
0.08	252.97	30.36	30.36	13.64	6.82
0.17	252.67	-0.30	30.06	13.50	13.57
0.25	252.71	0.04	30.10	13.52	13.51
0.33	252.68	-0.03	30.07	13.51	13.51
0.42	252.35	-0.33	29.74	13.36	13.43
0.50	252.59	0.24	29.98	13.47	13.41
0.58	252.42	-0.17	29.81	13.39	13.43
0.67	251.78	-0.64	29.17	13.10	13.25
0.75	253.52	1.74	30.91	13.89	13.49
0.83	252.63	-0.89	30.02	13.49	13.69
0.92	252.65	0.02	30.04	13.49	13.49
1.00	252.66	0.01	30.05	13.50	13.50
1.25	252.48	-0.18	29.87	13.42	13.46
1.50	252.57	0.09	29.96	13.46	13.44
1.75	252.53	-0.04	29.92	13.44	13.45
2.00	252.39	-0.14	29.78	13.38	13.41
2.25	252.50	0.11	29.89	13.43	13.40
2.50	252.36	-0.14	29.75	13.36	13.40
2.75	252.69	0.33	30.08	13.51	13.44
3.00	252.52	-0.17	29.91	13.44	13.47
4.00	252.38	-0.14	29.77	13.37	13.40
5.00	252.69	0.31	30.08	13.51	13.44
6.00	252.63	-0.06	30.02	13.49	13.50
7.00	252.26	-0.37	29.65	13.32	13.40
8.00	252.67	0.41	30.06	13.50	13.41
24.0	252.71	0.04	30.10	13.52	13.51
48.0	252.48	-0.23	29.87	13.42	13.47
72.0	252.35	-0.13	29.74	13.36	13.39
96.0	252.39	0.04	29.78	13.38	13.37

APPENDIX G: WATER ABSORPTION – NORMAL 7/81



APPENDIX G: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION MEASUREMENTS FOR SAMPLE F1

Time (hours)	Weight (g)	Difference in successive weighings (g)	Change in weight from initial weight (g)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	223.90	0.00	0.00	0.00	0.00
0.08	252.51	28.61	28.61	12.78	6.39
0.17	254.65	2.14	30.75	13.73	13.26
0.25	254.68	0.03	30.78	13.75	13.74
0.33	254.89	0.21	30.99	13.84	13.79
0.42	255.11	0.22	31.21	13.94	13.89
0.50	255.37	0.26	31.47	14.06	14.00
0.58	255.26	-0.11	31.36	14.01	14.03
0.67	255.32	0.06	31.42	14.03	14.02
0.75	255.35	0.03	31.45	14.05	14.04
0.83	255.34	-0.01	31.44	14.04	14.04
0.92	255.29	-0.05	31.39	14.02	14.03
1.00	255.19	-0.10	31.29	13.97	14.00
1.25	255.50	0.31	31.60	14.11	14.04
1.50	255.14	-0.36	31.24	13.95	14.03
1.75	255.05	-0.09	31.15	13.91	13.93
2.00	255.07	0.02	31.17	13.92	13.92
2.25	255.05	-0.02	31.15	13.91	13.92
2.50	255.00	-0.05	31.10	13.89	13.90
2.75	255.14	0.14	31.24	13.95	13.92
3.00	254.92	-0.22	31.02	13.85	13.90
4.00	255.03	0.11	31.13	13.90	13.88
5.00	254.97	-0.06	31.07	13.88	13.89
6.00	254.89	-0.08	30.99	13.84	13.86
7.00	254.73	-0.16	30.83	13.77	13.81
8.00	255.03	0.30	31.13	13.90	13.84
24.0	254.83	-0.20	30.93	13.81	13.86
48.0	254.92	0.09	31.02	13.85	13.83
72.0	254.77	-0.15	30.87	13.79	13.82
96.0	255.08	0.31	31.18	13.93	13.86

APPENDIX G: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION MEASUREMENTS FOR SAMPLE F2

Time (hours)	Weight (g)	Difference in successive weighings (g)	Change in weight from initial weight (g)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	230.82	0.00	0.00	0.00	0.00
0.08	260.02	29.20	29.20	12.65	6.33
0.17	261.68	1.66	30.86	13.37	13.01
0.25	261.45	-0.23	30.63	13.27	13.32
0.33	261.51	0.06	30.69	13.30	13.28
0.42	261.65	0.14	30.83	13.36	13.33
0.50	261.91	0.26	31.09	13.47	13.41
0.58	261.63	-0.28	30.81	13.35	13.41
0.67	261.49	-0.14	30.67	13.29	13.32
0.75	261.71	0.22	30.89	13.38	13.34
0.83	261.94	0.23	31.12	13.48	13.43
0.92	261.79	-0.15	30.97	13.42	13.45
1.00	261.66	-0.13	30.84	13.36	13.39
1.25	261.78	0.12	30.96	13.41	13.39
1.50	261.50	-0.28	30.68	13.29	13.35
1.75	261.57	0.07	30.75	13.32	13.31
2.00	261.61	0.04	30.79	13.34	13.33
2.25	261.50	-0.11	30.68	13.29	13.32
2.50	261.40	-0.10	30.58	13.25	13.27
2.75	261.70	0.30	30.88	13.38	13.31
3.00	261.53	-0.17	30.71	13.30	13.34
4.00	261.59	0.06	30.77	13.33	13.32
5.00	261.54	-0.05	30.72	13.31	13.32
6.00	261.41	-0.13	30.59	13.25	13.28
7.00	261.17	-0.24	30.35	13.15	13.20
8.00	261.64	0.47	30.82	13.35	13.25
24.0	261.48	-0.16	30.66	13.28	13.32
48.0	261.51	0.03	30.69	13.30	13.29
72.0	261.41	-0.10	30.59	13.25	13.27
96.0	261.69	0.28	30.87	13.37	13.31

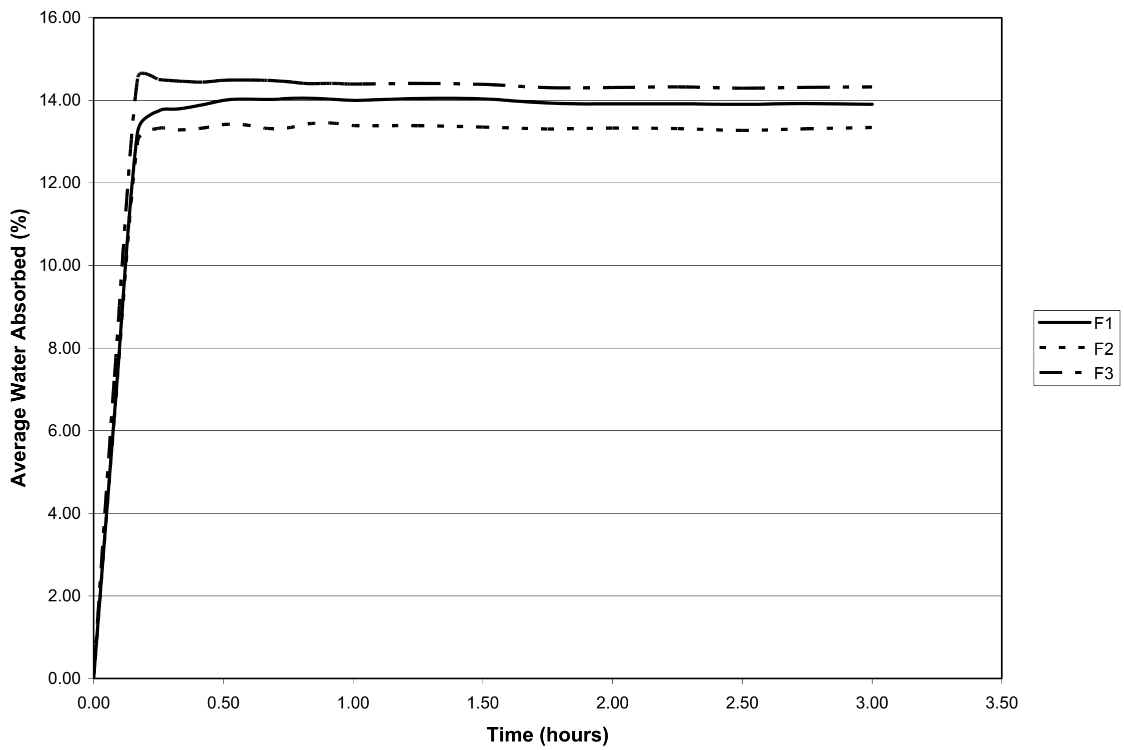
APPENDIX G: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION MEASUREMENTS FOR SAMPLE F3

Time (hours)	Weight (g)	Difference in successive weighings (g)	Change in weight from initial weight (g)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	232.51	0.00	0.00	0.00	0.00
0.08	266.49	33.98	33.98	14.61	7.31
0.17	266.23	-0.26	33.72	14.50	14.56
0.25	266.23	0.00	33.72	14.50	14.50
0.33	266.05	-0.18	33.54	14.43	14.46
0.42	266.12	0.07	33.61	14.46	14.44
0.50	266.26	0.14	33.75	14.52	14.49
0.58	266.15	-0.11	33.64	14.47	14.49
0.67	266.21	0.06	33.70	14.49	14.48
0.75	266.01	-0.20	33.50	14.41	14.45
0.83	265.99	-0.02	33.48	14.40	14.40
0.92	266.04	0.05	33.53	14.42	14.41
1.00	265.91	-0.13	33.40	14.36	14.39
1.25	266.11	0.20	33.60	14.45	14.41
1.50	265.81	-0.30	33.30	14.32	14.39
1.75	265.73	-0.08	33.22	14.29	14.30
2.00	265.83	0.10	33.32	14.33	14.31
2.25	265.80	-0.03	33.29	14.32	14.32
2.50	265.69	-0.11	33.18	14.27	14.29
2.75	265.89	0.20	33.38	14.36	14.31
3.00	265.75	-0.14	33.24	14.30	14.33
4.00	265.77	0.02	33.26	14.30	14.30
5.00	265.65	-0.12	33.14	14.25	14.28
6.00	265.51	-0.14	33.00	14.19	14.22
7.00	265.21	-0.30	32.70	14.06	14.13
8.00	265.57	0.36	33.06	14.22	14.14
24.0	265.50	-0.07	32.99	14.19	14.20
48.0	265.44	-0.06	32.93	14.16	14.18
72.0	265.21	-0.23	32.70	14.06	14.11
96.0	265.36	0.15	32.85	14.13	14.10

APPENDIX G: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION CURVES
FOR MODERATELY HYDRAULIC LIME SAMPLES WITH ACRYLIC EMULSION



APPENDIX G: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION MEASUREMENTS FOR SAMPLE S1

Time (hours)	Weight (g)	Difference in successive weighings (g)	Change in weight from initial weight (g)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	309.91	0.00	0.00	0.00	0.00
0.08	311.97	2.06	2.06	0.66	0.33
0.17	312.44	0.47	2.53	0.82	0.74
0.25	312.74	0.30	2.83	0.91	0.86
0.33	312.92	0.18	3.01	0.97	0.94
0.42	313.20	0.28	3.29	1.06	1.02
0.50	313.40	0.20	3.49	1.13	1.09
0.58	313.60	0.20	3.69	1.19	1.16
0.67	313.77	0.17	3.86	1.25	1.22
0.75	313.96	0.19	4.05	1.31	1.28
0.83	314.09	0.13	4.18	1.35	1.33
0.92	314.24	0.15	4.33	1.40	1.37
1.00	314.34	0.10	4.43	1.43	1.41
1.25	314.69	0.35	4.78	1.54	1.49
1.50	314.91	0.22	5.00	1.61	1.58
1.75	315.17	0.26	5.26	1.70	1.66
2.00	315.37	0.20	5.46	1.76	1.73
2.25	315.59	0.22	5.68	1.83	1.80
2.50	315.74	0.15	5.83	1.88	1.86
2.75	315.86	0.12	5.95	1.92	1.90
3.00	316.07	0.21	6.16	1.99	1.95
4.00	316.51	0.44	6.60	2.13	2.06
5.00	316.86	0.35	6.95	2.24	2.19
6.00	317.06	0.20	7.15	2.31	2.27
7.00	317.24	0.18	7.33	2.37	2.34
8.00	317.39	0.15	7.48	2.41	2.39
24.0	317.73	0.34	7.82	2.52	2.47
48.0	317.90	0.17	7.99	2.58	2.55
72.0	318.12	0.22	8.21	2.65	2.61
96.0	318.17	0.05	8.26	2.67	2.66
120.0	318.33	0.16	8.42	2.72	2.69
144.0	318.43	0.10	8.52	2.75	2.73
168.0	318.48	0.05	8.57	2.77	2.76

APPENDIX G: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION MEASUREMENTS FOR SAMPLE S2

Time (hours)	Weight (g)	Difference in successive weighings (g)	Change in weight from initial weight (g)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	312.23	0.00	0.00	0.00	0.00
0.08	314.28	2.05	2.05	0.66	0.33
0.17	314.76	0.48	2.53	0.81	0.73
0.25	315.14	0.38	2.91	0.93	0.87
0.33	315.38	0.24	3.15	1.01	0.97
0.42	315.66	0.28	3.43	1.10	1.05
0.50	315.79	0.13	3.56	1.14	1.12
0.58	315.97	0.18	3.74	1.20	1.17
0.67	316.15	0.18	3.92	1.26	1.23
0.75	316.40	0.25	4.17	1.34	1.30
0.83	316.45	0.05	4.22	1.35	1.34
0.92	316.58	0.13	4.35	1.39	1.37
1.00	316.73	0.15	4.50	1.44	1.42
1.25	317.10	0.37	4.87	1.56	1.50
1.50	317.29	0.19	5.06	1.62	1.59
1.75	317.56	0.27	5.33	1.71	1.66
2.00	317.73	0.17	5.50	1.76	1.73
2.25	317.92	0.19	5.69	1.82	1.79
2.50	318.11	0.19	5.88	1.88	1.85
2.75	318.23	0.12	6.00	1.92	1.90
3.00	318.43	0.20	6.20	1.99	1.95
4.00	318.86	0.43	6.63	2.12	2.05
5.00	319.25	0.39	7.02	2.25	2.19
6.00	319.43	0.18	7.20	2.31	2.28
7.00	319.61	0.18	7.38	2.36	2.33
8.00	319.72	0.11	7.49	2.40	2.38
24.0	320.06	0.34	7.83	2.51	2.45
48.0	320.31	0.25	8.08	2.59	2.55
72.0	320.48	0.17	8.25	2.64	2.62
96.0	320.58	0.10	8.35	2.67	2.66
120.0	320.63	0.05	8.40	2.69	2.68
144.0	320.84	0.21	8.61	2.76	2.72
168.0	320.87	0.03	8.64	2.77	2.76

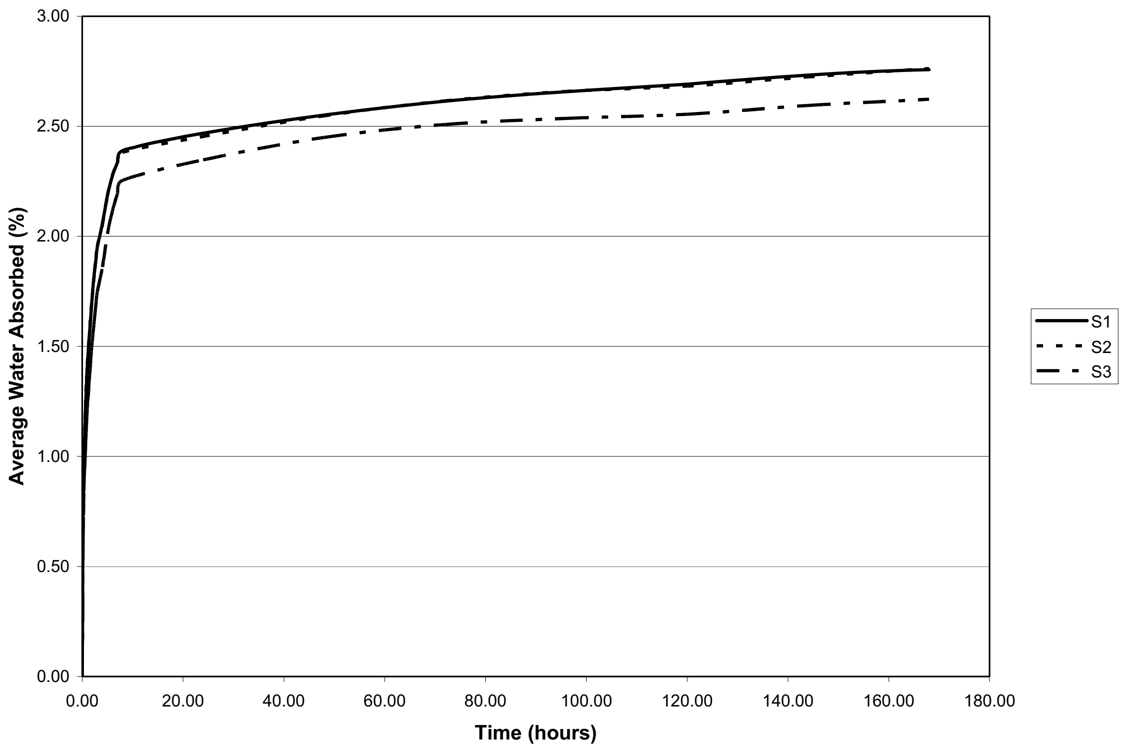
APPENDIX G: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION MEASUREMENTS FOR SAMPLE S3

Time (hours)	Weight (g)	Difference in successive weighings (g)	Change in weight from initial weight (g)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	323.38	0.00	0.00	0.00	0.00
0.08	325.18	1.80	1.80	0.56	0.28
0.17	325.59	0.41	2.21	0.68	0.62
0.25	325.91	0.32	2.53	0.78	0.73
0.33	326.30	0.39	2.92	0.90	0.84
0.42	326.42	0.12	3.04	0.94	0.92
0.50	326.54	0.12	3.16	0.98	0.96
0.58	326.67	0.13	3.29	1.02	1.00
0.67	326.86	0.19	3.48	1.08	1.05
0.75	326.98	0.12	3.60	1.11	1.09
0.83	327.13	0.15	3.75	1.16	1.14
0.92	327.26	0.13	3.88	1.20	1.18
1.00	327.40	0.14	4.02	1.24	1.22
1.25	327.75	0.35	4.37	1.35	1.30
1.50	327.94	0.19	4.56	1.41	1.38
1.75	328.24	0.30	4.86	1.50	1.46
2.00	328.41	0.17	5.03	1.56	1.53
2.25	328.59	0.18	5.21	1.61	1.58
2.50	328.79	0.20	5.41	1.67	1.64
2.75	328.96	0.17	5.58	1.73	1.70
3.00	329.11	0.15	5.73	1.77	1.75
4.00	329.68	0.57	6.30	1.95	1.86
5.00	330.09	0.41	6.71	2.07	2.01
6.00	330.35	0.26	6.97	2.16	2.12
7.00	330.59	0.24	7.21	2.23	2.19
8.00	330.75	0.16	7.37	2.28	2.25
24.0	331.19	0.44	7.81	2.42	2.35
48.0	331.41	0.22	8.03	2.48	2.45
72.0	331.57	0.16	8.19	2.53	2.51
96.0	331.59	0.02	8.21	2.54	2.54
120.0	331.69	0.10	8.31	2.57	2.55
144.0	331.85	0.16	8.47	2.62	2.59
168.0	331.87	0.02	8.49	2.63	2.62

APPENDIX G: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION CURVES
FOR CONNECTICUT BROWNSTONE SAMPLES



Appendix H: Drying rate – NORMAL 29/88

Drying Measurements for Sample A1

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight, W_d (g)	Residual water content, Q_i (%)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y (%)	Difference in moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
0.00	0.00	262.47	237.41	10.56	25.06	25.06	100.00	0.00	0.00	0.20
0.08	0.08	262.36	237.41	10.51	25.06	24.95	99.56	0.11	1.38	0.20
0.17	0.09	262.27	237.41	10.47	25.06	24.86	99.20	0.20	2.22	0.20
0.25	0.08	262.19	237.41	10.44	25.06	24.78	98.88	0.28	3.50	0.20
0.33	0.08	262.09	237.41	10.40	25.06	24.68	98.48	0.38	4.75	0.20
0.42	0.09	262.02	237.41	10.37	25.06	24.61	98.20	0.45	5.00	0.20
0.50	0.08	261.94	237.41	10.33	25.06	24.53	97.89	0.53	6.63	0.20
0.58	0.08	261.84	237.41	10.29	25.06	24.43	97.49	0.63	7.88	0.20
0.67	0.09	261.79	237.41	10.27	25.06	24.38	97.29	0.68	7.56	0.20
0.75	0.08	261.69	237.41	10.23	25.06	24.28	96.89	0.78	9.75	0.19
0.83	0.08	261.63	237.41	10.20	25.06	24.22	96.65	0.84	10.50	0.19
0.92	0.09	261.58	237.41	10.18	25.06	24.17	96.45	0.89	9.89	0.19
1.00	0.08	261.51	237.41	10.15	25.06	24.10	96.17	0.96	12.00	0.19
1.25	0.25	261.41	237.41	10.11	25.06	24.00	95.77	1.06	4.24	0.19
1.50	0.25	261.25	237.41	10.04	25.06	23.84	95.13	1.22	4.88	0.19
1.75	0.25	261.13	237.41	9.99	25.06	23.72	94.65	1.34	5.36	0.19
2.00	0.25	260.96	237.41	9.92	25.06	23.55	93.97	1.51	6.04	0.19

APPENDIX H: DRYING RATE – NORMAL 29/88

DRYING MEASUREMENTS FOR SAMPLE A1 (CONTINUED)

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight, W_d (g)	Residual water content, Q_i (%)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y (%)	Difference in moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
2.25	0.25	260.81	237.41	9.86	25.06	23.40	93.38	1.66	6.64	0.19
2.50	0.25	260.62	237.41	9.78	25.06	23.21	92.62	1.85	7.40	0.19
2.75	0.25	260.47	237.41	9.71	25.06	23.06	92.02	2.00	8.00	0.18
3.00	0.25	260.31	237.41	9.65	25.06	22.90	91.38	2.16	8.64	0.18
24.0	21.00	257.03	237.41	8.26	25.06	19.62	78.29	5.44	0.26	0.16
48.0	24.00	252.21	237.41	6.23	25.06	14.80	59.06	10.26	0.43	0.12
72.0	24.00	247.82	237.41	4.38	25.06	10.41	41.54	14.65	0.61	0.08
96.0	24.00	246.34	237.41	3.76	25.06	8.93	35.63	16.13	0.67	0.07
120.0	24.00	245.15	237.41	3.26	25.06	7.74	30.89	17.32	0.72	0.06
144.0	24.00	237.99	237.41	0.24	25.06	0.58	2.31	24.48	1.02	0.00
168.0	24.00	237.41	237.41	0.00	25.06	0.00	0.00	25.06	1.04	0.00
192.0	24.00	237.41	237.41	0.00	25.06	0.00	0.00	25.06	1.04	0.00

Shaded measurements were taken after sample was placed in the oven.

APPENDIX H: DRYING RATE – NORMAL 29/88

DRYING MEASUREMENTS FOR SAMPLE A2

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight, W_d (g)	Residual water content, Q_i (%)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y (%)	Difference in moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
0.00	0.00	269.76	243.58	10.75	26.18	26.18	100.00	0.00	0.00	0.21
0.08	0.08	269.66	243.58	10.71	26.18	26.08	99.62	0.10	1.25	0.21
0.17	0.09	269.57	243.58	10.67	26.18	25.99	99.27	0.19	2.11	0.21
0.25	0.08	269.48	243.58	10.63	26.18	25.90	98.93	0.28	3.50	0.21
0.33	0.08	269.39	243.58	10.60	26.18	25.81	98.59	0.37	4.63	0.21
0.42	0.09	269.31	243.58	10.56	26.18	25.73	98.28	0.45	5.00	0.21
0.50	0.08	269.23	243.58	10.53	26.18	25.65	97.98	0.53	6.62	0.21
0.58	0.08	269.15	243.58	10.50	26.18	25.57	97.67	0.61	7.63	0.20
0.67	0.09	269.07	243.58	10.46	26.18	25.49	97.36	0.69	7.67	0.20
0.75	0.08	268.99	243.58	10.43	26.18	25.41	97.06	0.77	9.62	0.20
0.83	0.08	268.93	243.58	10.41	26.18	25.35	96.83	0.83	10.37	0.20
0.92	0.09	268.86	243.58	10.38	26.18	25.28	96.56	0.90	10.00	0.20
1.00	0.08	268.80	243.58	10.35	26.18	25.22	96.33	0.96	12.00	0.20
1.25	0.25	268.67	243.58	10.30	26.18	25.09	95.84	1.09	4.36	0.20
1.50	0.25	268.52	243.58	10.24	26.18	24.94	95.26	1.24	4.96	0.20
1.75	0.25	268.39	243.58	10.19	26.18	24.81	94.77	1.37	5.48	0.20
2.00	0.25	268.23	243.58	10.12	26.18	24.65	94.16	1.53	6.12	0.20

Appendix H: Drying rate – NORMAL 29/88

Drying Measurements for Sample A2 (continued)

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight, W_d (g)	Residual water content, Q_i (%)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y (%)	Difference in moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
2.25	0.25	268.08	243.58	10.06	26.18	24.50	93.58	1.68	6.72	0.20
2.50	0.25	267.93	243.58	10.00	26.18	24.35	93.01	1.83	7.32	0.19
2.75	0.25	267.77	243.58	9.93	26.18	24.19	92.40	1.99	7.96	0.19
3.00	0.25	267.61	243.58	9.87	26.18	24.03	91.79	2.15	8.60	0.19
24.0	21.00	264.87	243.58	8.74	26.18	21.29	81.32	4.89	0.23	0.17
48.0	24.00	260.20	243.58	6.82	26.18	16.62	63.48	9.56	0.40	0.13
72.0	24.00	256.07	243.58	5.13	26.18	12.49	47.71	13.69	0.57	0.10
96.0	24.00	254.40	243.58	4.44	26.18	10.82	41.33	15.36	0.64	0.09
120.0	24.00	252.96	243.58	3.85	26.18	9.38	35.83	16.80	0.70	0.08
144.0	24.00	244.31	243.58	0.30	26.18	0.73	2.79	25.45	1.06	0.01
168.0	24.00	243.58	243.58	0.00	26.18	0.00	0.00	26.18	1.09	0.00
192.0	24.00	243.58	243.58	0.00	26.18	0.00	0.00	26.18	1.09	0.00

Shaded measurements were taken after sample was placed in the oven.

Appendix H: Drying rate – NORMAL 29/88

Drying Measurements for Sample A3

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight, W_d (g)	Residual water content, Q_i (%)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y (%)	Difference in moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
0.00	0.00	263.46	237.77	10.80	25.69	25.69	100.00	0.00	0.00	0.21
0.08	0.08	263.33	237.77	10.75	25.69	25.56	99.49	0.13	1.62	0.20
0.17	0.09	263.22	237.77	10.70	25.69	25.45	99.07	0.24	2.67	0.20
0.25	0.08	263.12	237.77	10.66	25.69	25.35	98.68	0.34	4.25	0.20
0.33	0.08	263.03	237.77	10.62	25.69	25.26	98.33	0.43	5.38	0.20
0.42	0.09	262.95	237.77	10.59	25.69	25.18	98.01	0.51	5.67	0.20
0.50	0.08	262.86	237.77	10.55	25.69	25.09	97.66	0.60	7.50	0.20
0.58	0.08	262.78	237.77	10.52	25.69	25.01	97.35	0.68	8.50	0.20
0.67	0.09	262.64	237.77	10.46	25.69	24.87	96.81	0.82	9.11	0.20
0.75	0.08	262.62	237.77	10.45	25.69	24.85	96.73	0.84	10.50	0.20
0.83	0.08	262.54	237.77	10.42	25.69	24.77	96.42	0.92	11.50	0.20
0.92	0.09	262.48	237.77	10.39	25.69	24.71	96.19	0.98	10.89	0.20
1.00	0.08	262.40	237.77	10.36	25.69	24.63	95.87	1.06	13.25	0.20
1.25	0.25	262.29	237.77	10.31	25.69	24.52	95.45	1.17	4.68	0.20
1.50	0.25	262.12	237.77	10.24	25.69	24.35	94.78	1.34	5.36	0.19
1.75	0.25	261.99	237.77	10.19	25.69	24.22	94.28	1.47	5.88	0.19
2.00	0.25	261.81	237.77	10.11	25.69	24.04	93.58	1.65	6.60	0.19

Appendix H: Drying rate – NORMAL 29/88

Drying Measurements for Sample A3 (continued)

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight, W_d (g)	Residual water content, Q_i (%)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y (%)	Difference in moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
2.25	0.25	261.63	237.77	10.03	25.69	23.86	92.88	1.83	7.32	0.19
2.50	0.25	261.46	237.77	9.96	25.69	23.69	92.21	2.00	8.00	0.19
2.75	0.25	261.28	237.77	9.89	25.69	23.51	91.51	2.18	8.72	0.19
3.00	0.25	261.11	237.77	9.82	25.69	23.34	90.85	2.35	9.40	0.19
24.0	21.00	258.03	237.77	8.52	25.69	20.26	78.86	5.43	0.26	0.16
48.0	24.00	253.49	237.77	6.61	25.69	15.72	61.19	9.97	0.42	0.13
72.0	24.00	249.94	237.77	5.12	25.69	12.17	47.37	13.52	0.56	0.10
96.0	24.00	248.22	237.77	4.40	25.69	10.45	40.68	15.24	0.63	0.08
120.0	24.00	246.83	237.77	3.81	25.69	9.06	35.27	16.63	0.69	0.07
144.0	24.00	238.28	237.77	0.21	25.69	0.51	1.99	25.18	1.05	0.00
168.0	24.00	237.77	237.77	0.00	25.69	0.00	0.00	25.69	1.07	0.00
192.0	24.00	237.77	237.77	0.00	25.69	0.00	0.00	25.69	1.07	0.00

Shaded measurements were taken after sample was placed in the oven.

Appendix H: Drying rate – NORMAL 29/88

Drying Measurements for Sample B1

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight, W_d (g)	Residual water content, Q_i (%)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y (%)	Difference in moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
0.00	0.00	275.01	252.20	9.04	22.81	22.81	100.00	0.00	0.00	0.18
0.08	0.08	274.87	252.20	8.99	22.81	22.67	99.39	0.14	1.75	0.18
0.17	0.09	274.74	252.20	8.94	22.81	22.54	98.82	0.27	3.00	0.18
0.25	0.08	274.66	252.20	8.91	22.81	22.46	98.47	0.35	4.37	0.18
0.33	0.08	274.61	252.20	8.89	22.81	22.41	98.25	0.40	5.00	0.18
0.42	0.09	274.53	252.20	8.85	22.81	22.33	97.90	0.48	5.33	0.18
0.50	0.08	274.42	252.20	8.81	22.81	22.22	97.41	0.59	7.37	0.18
0.58	0.08	274.41	252.20	8.81	22.81	22.21	97.37	0.60	7.50	0.18
0.67	0.09	274.33	252.20	8.77	22.81	22.13	97.02	0.68	7.56	0.18
0.75	0.08	274.27	252.20	8.75	22.81	22.07	96.76	0.74	9.25	0.18
0.83	0.08	274.20	252.20	8.72	22.81	22.00	96.45	0.81	10.13	0.18
0.92	0.09	274.11	252.20	8.69	22.81	21.91	96.05	0.90	10.00	0.18
1.00	0.08	274.06	252.20	8.67	22.81	21.86	95.84	0.95	11.87	0.17
1.25	0.25	273.92	252.20	8.61	22.81	21.72	95.22	1.09	4.36	0.17
1.50	0.25	273.81	252.20	8.57	22.81	21.61	94.74	1.20	4.80	0.17
1.75	0.25	273.63	252.20	8.50	22.81	21.43	93.95	1.38	5.52	0.17
2.00	0.25	273.44	252.20	8.42	22.81	21.24	93.12	1.57	6.28	0.17

Appendix H: Drying rate – NORMAL 29/88

Drying Measurements for Sample B1 (continued)

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight, W_d (g)	Residual water content, Q_i (%)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y (%)	Difference in moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
2.25	0.25	273.30	252.20	8.37	22.81	21.10	92.50	1.71	6.84	0.17
2.50	0.25	273.19	252.20	8.32	22.81	20.99	92.02	1.82	7.28	0.17
2.75	0.25	273.07	252.20	8.28	22.81	20.87	91.49	1.94	7.76	0.17
3.00	0.25	272.98	252.20	8.24	22.81	20.78	91.10	2.03	8.12	0.17
24.0	21.00	269.83	252.20	6.99	22.81	17.63	77.29	5.18	0.25	0.14
48.0	24.00	265.84	252.20	5.41	22.81	13.64	59.80	9.17	0.38	0.11
72.0	24.00	263.24	252.20	4.38	22.81	11.04	48.40	11.77	0.49	0.09
96.0	24.00	261.87	252.20	3.83	22.81	9.67	42.39	13.14	0.55	0.08
120.0	24.00	260.91	252.20	3.45	22.81	8.71	38.19	14.10	0.59	0.07
144.0	24.00	253.20	252.20	0.40	22.81	1.00	4.38	21.81	0.91	0.01
168.0	24.00	252.21	252.20	0.00	22.81	0.01	0.04	22.80	0.95	0.00
192.0	24.00	252.20	252.20	0.00	22.81	0.00	0.00	22.81	0.95	0.00

Shaded measurements were taken after sample was placed in the oven.

Appendix H: Drying rate – NORMAL 29/88

Drying Measurements for Sample B2

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight, W_d (g)	Residual water content, Q_i (%)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y (%)	Difference in moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
0.00	0.00	269.95	246.98	9.30	22.97	22.97	100.00	0.00	0.00	0.18
0.08	0.08	269.83	246.98	9.25	22.97	22.85	99.48	0.12	1.50	0.18
0.17	0.09	269.73	246.98	9.21	22.97	22.75	99.04	0.22	2.44	0.18
0.25	0.08	269.67	246.98	9.19	22.97	22.69	98.78	0.28	3.50	0.18
0.33	0.08	269.60	246.98	9.16	22.97	22.62	98.48	0.35	4.37	0.18
0.42	0.09	269.53	246.98	9.13	22.97	22.55	98.17	0.42	4.67	0.18
0.50	0.08	269.47	246.98	9.11	22.97	22.49	97.91	0.48	6.00	0.18
0.58	0.08	269.39	246.98	9.07	22.97	22.41	97.56	0.56	7.00	0.18
0.67	0.09	269.33	246.98	9.05	22.97	22.35	97.30	0.62	6.89	0.18
0.75	0.08	269.26	246.98	9.02	22.97	22.28	97.00	0.69	8.62	0.18
0.83	0.08	269.21	246.98	9.00	22.97	22.23	96.78	0.74	9.25	0.18
0.92	0.09	269.12	246.98	8.96	22.97	22.14	96.39	0.83	9.22	0.18
1.00	0.08	269.07	246.98	8.94	22.97	22.09	96.17	0.88	11.00	0.18
1.25	0.25	268.94	246.98	8.89	22.97	21.96	95.60	1.01	4.04	0.18
1.50	0.25	268.85	246.98	8.85	22.97	21.87	95.21	1.10	4.40	0.17
1.75	0.25	268.70	246.98	8.79	22.97	21.72	94.56	1.25	5.00	0.17
2.00	0.25	268.53	246.98	8.73	22.97	21.55	93.82	1.42	5.68	0.17

APPENDIX H: DRYING RATE – NORMAL 29/88

DRYING MEASUREMENTS FOR SAMPLE B2 (CONTINUED)

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight, W_d (g)	Residual water content, Q_i (%)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y (%)	Difference in moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
2.25	0.25	268.40	246.98	8.67	22.97	21.42	93.25	1.55	6.20	0.17
2.50	0.25	268.28	246.98	8.62	22.97	21.30	92.73	1.67	6.68	0.17
2.75	0.25	268.17	246.98	8.58	22.97	21.19	92.25	1.78	7.12	0.17
3.00	0.25	268.08	246.98	8.54	22.97	21.10	91.86	1.87	7.48	0.17
24.0	21.00	265.76	246.98	7.60	22.97	18.78	81.76	4.19	0.20	0.15
48.0	24.00	262.06	246.98	6.11	22.97	15.08	65.65	7.89	0.33	0.12
72.0	24.00	259.44	246.98	5.04	22.97	12.46	54.24	10.51	0.44	0.10
96.0	24.00	257.86	246.98	4.41	22.97	10.88	47.37	12.09	0.50	0.09
120.0	24.00	256.64	246.98	3.91	22.97	9.66	42.05	13.31	0.55	0.08
144.0	24.00	247.74	246.98	0.31	22.97	0.76	3.31	22.21	0.93	0.01
168.0	24.00	246.98	246.98	0.00	22.97	0.00	0.00	22.97	0.96	0.00
192.0	24.00	246.98	246.98	0.00	22.97	0.00	0.00	22.97	0.96	0.00

Shaded measurements were taken after sample was placed in the oven.

APPENDIX H: DRYING RATE – NORMAL 29/88

DRYING MEASUREMENTS FOR SAMPLE B3

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight, W_d (g)	Residual water content, Q_i (%)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y (%)	Difference in moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
0.00	0.00	274.35	250.85	9.37	23.50	23.50	100.00	0.00	0.00	0.19
0.08	0.08	274.23	250.85	9.32	23.50	23.38	99.49	0.12	1.50	0.19
0.17	0.09	274.12	250.85	9.28	23.50	23.27	99.02	0.23	2.56	0.19
0.25	0.08	274.05	250.85	9.25	23.50	23.20	98.72	0.30	3.75	0.19
0.33	0.08	273.99	250.85	9.22	23.50	23.14	98.47	0.36	4.50	0.19
0.42	0.09	273.90	250.85	9.19	23.50	23.05	98.09	0.45	5.00	0.18
0.50	0.08	273.83	250.85	9.16	23.50	22.98	97.79	0.52	6.50	0.18
0.58	0.08	273.76	250.85	9.13	23.50	22.91	97.49	0.59	7.38	0.18
0.67	0.09	273.68	250.85	9.10	23.50	22.83	97.15	0.67	7.44	0.18
0.75	0.08	273.61	250.85	9.07	23.50	22.76	96.85	0.74	9.25	0.18
0.83	0.08	273.54	250.85	9.05	23.50	22.69	96.55	0.81	10.13	0.18
0.92	0.09	273.46	250.85	9.01	23.50	22.61	96.21	0.89	9.89	0.18
1.00	0.08	273.39	250.85	8.99	23.50	22.54	95.91	0.96	12.00	0.18
1.25	0.25	273.25	250.85	8.93	23.50	22.40	95.32	1.10	4.40	0.18
1.50	0.25	273.15	250.85	8.89	23.50	22.30	94.89	1.20	4.80	0.18
1.75	0.25	272.98	250.85	8.82	23.50	22.13	94.17	1.37	5.48	0.18
2.00	0.25	272.81	250.85	8.75	23.50	21.96	93.45	1.54	6.16	0.18

APPENDIX H: DRYING RATE – NORMAL 29/88

DRYING MEASUREMENTS FOR SAMPLE B3 (CONTINUED)

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight, W_d (g)	Residual water content, Q_i (%)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y (%)	Difference in moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
2.25	0.25	272.68	250.85	8.70	23.50	21.83	92.89	1.67	6.68	0.17
2.50	0.25	272.55	250.85	8.65	23.50	21.70	92.34	1.80	7.20	0.17
2.75	0.25	272.41	250.85	8.59	23.50	21.56	91.74	1.94	7.76	0.17
3.00	0.25	272.32	250.85	8.56	23.50	21.47	91.36	2.03	8.12	0.17
24.0	21.00	269.76	250.85	7.54	23.50	18.91	80.47	4.59	0.22	0.15
48.0	24.00	266.22	250.85	6.13	23.50	15.37	65.40	8.13	0.34	0.12
72.0	24.00	263.51	250.85	5.05	23.50	12.66	53.87	10.84	0.45	0.10
96.0	24.00	261.90	250.85	4.41	23.50	11.05	47.02	12.45	0.52	0.09
120.0	24.00	260.62	250.85	3.89	23.50	9.77	41.57	13.73	0.57	0.08
144.0	24.00	251.16	250.85	0.12	23.50	0.31	1.32	23.19	0.97	0.00
168.0	24.00	250.85	250.85	0.00	23.50	0.00	0.00	23.50	0.98	0.00
192.0	24.00	250.85	250.85	0.00	23.50	0.00	0.00	23.50	0.98	0.00

Shaded measurements were taken after sample was placed in the oven.

APPENDIX H: DRYING RATE – NORMAL 29/88

DRYING MEASUREMENTS FOR SAMPLE C1

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight, W_d (g)	Residual water content, Q_i (%)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y (%)	Difference in moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
0.00	0.00	278.04	251.23	10.67	26.81	26.81	100.00	0.00	0.00	0.21
0.08	0.08	277.89	251.23	10.61	26.81	26.66	99.44	0.15	1.88	0.21
0.17	0.09	277.80	251.23	10.58	26.81	26.57	99.10	0.24	2.67	0.21
0.25	0.08	277.75	251.23	10.56	26.81	26.52	98.92	0.29	3.63	0.21
0.33	0.08	277.67	251.23	10.52	26.81	26.44	98.62	0.37	4.63	0.21
0.42	0.09	277.62	251.23	10.50	26.81	26.39	98.43	0.42	4.67	0.21
0.50	0.08	277.57	251.23	10.48	26.81	26.34	98.25	0.47	5.88	0.21
0.58	0.08	277.50	251.23	10.46	26.81	26.27	97.99	0.54	6.75	0.21
0.67	0.09	277.45	251.23	10.44	26.81	26.22	97.80	0.59	6.56	0.21
0.75	0.08	277.40	251.23	10.42	26.81	26.17	97.61	0.64	8.00	0.21
0.83	0.08	277.34	251.23	10.39	26.81	26.11	97.39	0.70	8.75	0.21
0.92	0.09	277.29	251.23	10.37	26.81	26.06	97.20	0.75	8.33	0.21
1.00	0.08	277.25	251.23	10.36	26.81	26.02	97.05	0.79	9.88	0.21
1.25	0.25	277.14	251.23	10.31	26.81	25.91	96.64	0.90	3.60	0.21
1.50	0.25	277.09	251.23	10.29	26.81	25.86	96.46	0.95	3.80	0.21
1.75	0.25	276.96	251.23	10.24	26.81	25.73	95.97	1.08	4.32	0.21
2.00	0.25	276.83	251.23	10.19	26.81	25.60	95.49	1.21	4.84	0.20

DRYING MEASUREMENTS FOR SAMPLE C1 (CONTINUED)

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight, W_d (g)	Residual water content, Q_i (%)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y (%)	Difference in moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
2.25	0.25	276.75	251.23	10.16	26.81	25.52	95.19	1.29	5.16	0.20
2.50	0.25	276.66	251.23	10.12	26.81	25.43	94.85	1.38	5.52	0.20
2.75	0.25	276.57	251.23	10.09	26.81	25.34	94.52	1.47	5.88	0.20
3.00	0.25	276.49	251.23	10.05	26.81	25.26	94.22	1.55	6.20	0.20
24.0	21.00	272.10	251.23	8.31	26.81	20.87	77.84	5.94	0.28	0.17
48.0	24.00	263.30	251.23	4.80	26.81	12.07	45.02	14.74	0.61	0.10
72.0	24.00	257.68	251.23	2.57	26.81	6.45	24.06	20.36	0.85	0.05
96.0	24.00	255.37	251.23	1.65	26.81	4.14	15.44	22.67	0.94	0.03
120.0	24.00	254.18	251.23	1.17	26.81	2.95	11.00	23.86	0.99	0.02
144.0	24.00	251.23	251.23	0.00	26.81	0.00	0.00	26.81	1.12	0.00
168.0	24.00	251.23	251.23	0.00	26.81	0.00	0.00	26.81	1.12	0.00

Shaded measurements were taken after sample was placed in the oven.

APPENDIX H: DRYING RATE – NORMAL 29/88

DRYING MEASUREMENTS FOR SAMPLE C2

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight, W_d (g)	Residual water content, Q_i (%)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y (%)	Difference in moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
0.00	0.00	288.21	260.82	10.50	27.39	27.39	100.00	0.00	0.00	0.22
0.08	0.08	288.09	260.82	10.46	27.39	27.27	99.56	0.12	1.50	0.22
0.17	0.09	287.99	260.82	10.42	27.39	27.17	99.20	0.22	2.44	0.22
0.25	0.08	287.93	260.82	10.39	27.39	27.11	98.98	0.28	3.50	0.22
0.33	0.08	287.84	260.82	10.36	27.39	27.02	98.65	0.37	4.63	0.22
0.42	0.09	287.81	260.82	10.35	27.39	26.99	98.54	0.40	4.44	0.22
0.50	0.08	287.76	260.82	10.33	27.39	26.94	98.36	0.45	5.62	0.22
0.58	0.08	287.68	260.82	10.30	27.39	26.86	98.06	0.53	6.62	0.21
0.67	0.09	287.64	260.82	10.28	27.39	26.82	97.92	0.57	6.33	0.21
0.75	0.08	287.59	260.82	10.26	27.39	26.77	97.74	0.62	7.75	0.21
0.83	0.08	287.53	260.82	10.24	27.39	26.71	97.52	0.68	8.50	0.21
0.92	0.09	287.49	260.82	10.23	27.39	26.67	97.37	0.72	8.00	0.21
1.00	0.08	287.44	260.82	10.21	27.39	26.62	97.19	0.77	9.62	0.21
1.25	0.25	287.37	260.82	10.18	27.39	26.55	96.93	0.84	3.36	0.21
1.50	0.25	287.28	260.82	10.14	27.39	26.46	96.60	0.93	3.72	0.21
1.75	0.25	287.20	260.82	10.11	27.39	26.38	96.31	1.01	4.04	0.21
2.00	0.25	287.07	260.82	10.06	27.39	26.25	95.84	1.14	4.56	0.21

Appendix H: Drying rate – NORMAL 29/88

Drying Measurements for Sample C2 (continued)

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight, W_d (g)	Residual water content, Q_i (%)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y (%)	Difference in moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
2.25	0.25	287.00	260.82	10.04	27.39	26.18	95.58	1.21	4.84	0.21
2.50	0.25	286.93	260.82	10.01	27.39	26.11	95.33	1.28	5.12	0.21
2.75	0.25	286.86	260.82	9.98	27.39	26.04	95.07	1.35	5.40	0.21
3.00	0.25	286.79	260.82	9.96	27.39	25.97	94.82	1.42	5.68	0.21
24.0	21.00	283.05	260.82	8.52	27.39	22.23	81.16	5.16	0.25	0.18
48.0	24.00	275.53	260.82	5.64	27.39	14.71	53.71	12.68	0.53	0.12
72.0	24.00	269.38	260.82	3.28	27.39	8.56	31.25	18.83	0.78	0.07
96.0	24.00	266.48	260.82	2.17	27.39	5.66	20.66	21.73	0.91	0.05
120.0	24.00	264.90	260.82	1.56	27.39	4.08	14.90	23.31	0.97	0.03
144.0	24.00	260.82	260.82	0.00	27.39	0.00	0.00	27.39	1.14	0.00
168.0	24.00	260.82	260.82	0.00	27.39	0.00	0.00	27.39	1.14	0.00

Shaded measurements were taken after sample was placed in the oven.

APPENDIX H: DRYING RATE – NORMAL 29/88

DRYING MEASUREMENTS FOR SAMPLE C3

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight, W_d (g)	Residual water content, Q_i (%)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y (%)	Difference in moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
0.00	0.00	278.06	251.09	10.74	26.97	26.97	100.00	0.00	0.00	0.22
0.08	0.08	277.94	251.09	10.69	26.97	26.85	99.56	0.12	1.50	0.21
0.17	0.09	277.87	251.09	10.67	26.97	26.78	99.30	0.19	2.11	0.21
0.25	0.08	277.79	251.09	10.63	26.97	26.70	99.00	0.27	3.37	0.21
0.33	0.08	277.70	251.09	10.60	26.97	26.61	98.67	0.36	4.50	0.21
0.42	0.09	277.65	251.09	10.58	26.97	26.56	98.48	0.41	4.56	0.21
0.50	0.08	277.61	251.09	10.56	26.97	26.52	98.33	0.45	5.62	0.21
0.58	0.08	277.53	251.09	10.53	26.97	26.44	98.03	0.53	6.63	0.21
0.67	0.09	277.48	251.09	10.51	26.97	26.39	97.85	0.58	6.44	0.21
0.75	0.08	277.44	251.09	10.49	26.97	26.35	97.70	0.62	7.75	0.21
0.83	0.08	277.37	251.09	10.47	26.97	26.28	97.44	0.69	8.62	0.21
0.92	0.09	277.32	251.09	10.45	26.97	26.23	97.26	0.74	8.22	0.21
1.00	0.08	277.27	251.09	10.43	26.97	26.18	97.07	0.79	9.88	0.21
1.25	0.25	277.18	251.09	10.39	26.97	26.09	96.74	0.88	3.52	0.21
1.50	0.25	277.08	251.09	10.35	26.97	25.99	96.37	0.98	3.92	0.21
1.75	0.25	276.99	251.09	10.32	26.97	25.90	96.03	1.07	4.28	0.21
2.00	0.25	276.86	251.09	10.26	26.97	25.77	95.55	1.20	4.80	0.21

APPENDIX H: DRYING RATE – NORMAL 29/88

DRYING MEASUREMENTS FOR SAMPLE C3 (CONTINUED)

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight, W_d (g)	Residual water content, Q_i (%)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y (%)	Difference in moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
2.25	0.25	276.78	251.09	10.23	26.97	25.69	95.25	1.28	5.12	0.21
2.50	0.25	276.71	251.09	10.20	26.97	25.62	94.99	1.35	5.40	0.20
2.75	0.25	276.64	251.09	10.18	26.97	25.55	94.73	1.42	5.68	0.20
3.00	0.25	276.56	251.09	10.14	26.97	25.47	94.44	1.50	6.00	0.20
24.0	21.00	272.26	251.09	8.43	26.97	21.17	78.49	5.80	0.28	0.17
48.0	24.00	265.25	251.09	5.64	26.97	14.16	52.50	12.81	0.53	0.11
72.0	24.00	259.62	251.09	3.40	26.97	8.53	31.63	18.44	0.77	0.07
96.0	24.00	256.69	251.09	2.23	26.97	5.60	20.76	21.37	0.89	0.04
120.0	24.00	255.00	251.09	1.56	26.97	3.91	14.50	23.06	0.96	0.03
144.0	24.00	251.09	251.09	0.00	26.97	0.00	0.00	26.97	1.12	0.00
168.0	24.00	251.09	251.09	0.00	26.97	0.00	0.00	26.97	1.12	0.00

Shaded measurements were taken after sample was placed in the oven.

APPENDIX H: DRYING RATE – NORMAL 29/88

DRYING MEASUREMENTS FOR SAMPLE D1

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight, W_d (g)	Residual water content, Q_i (%)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y (%)	Difference in moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
0.00	0.00	255.42	227.08	12.48	28.34	28.34	100.00	0.00	0.00	0.23
0.08	0.08	255.24	227.08	12.40	28.34	28.16	99.36	0.18	2.25	0.23
0.17	0.09	255.10	227.08	12.34	28.34	28.02	98.87	0.32	3.56	0.22
0.25	0.08	254.98	227.08	12.29	28.34	27.90	98.45	0.44	5.50	0.22
0.33	0.08	254.87	227.08	12.24	28.34	27.79	98.06	0.55	6.87	0.22
0.42	0.09	254.76	227.08	12.19	28.34	27.68	97.67	0.66	7.33	0.22
0.50	0.08	254.66	227.08	12.15	28.34	27.58	97.32	0.76	9.50	0.22
0.58	0.08	254.56	227.08	12.10	28.34	27.48	96.97	0.86	10.75	0.22
0.67	0.09	254.47	227.08	12.06	28.34	27.39	96.65	0.95	10.56	0.22
0.75	0.08	254.40	227.08	12.03	28.34	27.32	96.40	1.02	12.75	0.22
0.83	0.08	254.29	227.08	11.98	28.34	27.21	96.01	1.13	14.13	0.22
0.92	0.09	254.22	227.08	11.95	28.34	27.14	95.77	1.20	13.33	0.22
1.00	0.08	254.11	227.08	11.90	28.34	27.03	95.38	1.31	16.37	0.22
1.25	0.25	253.92	227.08	11.82	28.34	26.84	94.71	1.50	6.00	0.21
1.50	0.25	253.75	227.08	11.74	28.34	26.67	94.11	1.67	6.68	0.21
1.75	0.25	253.60	227.08	11.68	28.34	26.52	93.58	1.82	7.28	0.21
2.00	0.25	253.43	227.08	11.60	28.34	26.35	92.98	1.99	7.96	0.21

APPENDIX H: DRYING RATE – NORMAL 29/88

DRYING MEASUREMENTS FOR SAMPLE D1 (CONTINUED)

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight, W_d (g)	Residual water content, Q_i (%)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y (%)	Difference in moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
2.25	0.25	253.28	227.08	11.54	28.34	26.20	92.45	2.14	8.56	0.21
2.50	0.25	253.12	227.08	11.47	28.34	26.04	91.88	2.30	9.20	0.21
2.75	0.25	252.97	227.08	11.40	28.34	25.89	91.35	2.45	9.80	0.21
3.00	0.25	252.83	227.08	11.34	28.34	25.75	90.86	2.59	10.36	0.21
24.0	21.00	243.37	227.08	7.17	28.34	16.29	57.48	12.05	0.57	0.13
48.0	24.00	234.90	227.08	3.44	28.34	7.82	27.59	20.52	0.85	0.06
72.0	24.00	231.93	227.08	2.14	28.34	4.85	17.11	23.49	0.98	0.04
96.0	24.00	230.44	227.08	1.48	28.34	3.36	11.86	24.98	1.04	0.03
120.0	24.00	229.81	227.08	1.20	28.34	2.73	9.63	25.61	1.07	0.02
144.0	24.00	227.08	227.08	0.00	28.34	0.00	0.00	28.34	1.18	0.00
168.0	24.00	227.08	227.08	0.00	28.34	0.00	0.00	28.34	1.18	0.00

Shaded measurements were taken after sample was placed in the oven.

Appendix H: Drying rate – NORMAL 29/88

Drying Measurements for Sample D2

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight, W_d (g)	Residual water content, Q_i (%)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y (%)	Difference in moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
0.00	0.00	260.72	231.34	12.70	29.38	29.38	100.00	0.00	0.00	0.24
0.08	0.08	260.58	231.34	12.64	29.38	29.24	99.52	0.14	1.75	0.23
0.17	0.09	260.46	231.34	12.59	29.38	29.12	99.12	0.26	2.89	0.23
0.25	0.08	260.36	231.34	12.54	29.38	29.02	98.77	0.36	4.50	0.23
0.33	0.08	260.24	231.34	12.49	29.38	28.90	98.37	0.48	6.00	0.23
0.42	0.09	260.12	231.34	12.44	29.38	28.78	97.96	0.60	6.67	0.23
0.50	0.08	260.02	231.34	12.40	29.38	28.68	97.62	0.70	8.75	0.23
0.58	0.08	259.93	231.34	12.36	29.38	28.59	97.31	0.79	9.88	0.23
0.67	0.09	259.85	231.34	12.32	29.38	28.51	97.04	0.87	9.67	0.23
0.75	0.08	259.76	231.34	12.28	29.38	28.42	96.73	0.96	12.00	0.23
0.83	0.08	259.69	231.34	12.25	29.38	28.35	96.49	1.03	12.88	0.23
0.92	0.09	259.59	231.34	12.21	29.38	28.25	96.15	1.13	12.56	0.23
1.00	0.08	259.48	231.34	12.16	29.38	28.14	95.78	1.24	15.50	0.23
1.25	0.25	259.36	231.34	12.11	29.38	28.02	95.37	1.36	5.44	0.22
1.50	0.25	259.23	231.34	12.06	29.38	27.89	94.93	1.49	5.96	0.22
1.75	0.25	259.07	231.34	11.99	29.38	27.73	94.38	1.65	6.60	0.22
2.00	0.25	258.96	231.34	11.94	29.38	27.62	94.01	1.76	7.04	0.22

Appendix H: Drying rate – NORMAL 29/88

Drying Measurements for Sample D2 (continued)

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight, W_d (g)	Residual water content, Q_i (%)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y (%)	Difference in moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
2.25	0.25	258.85	231.34	11.89	29.38	27.51	93.64	1.87	7.48	0.22
2.50	0.25	258.74	231.34	11.84	29.38	27.40	93.26	1.98	7.92	0.22
2.75	0.25	258.62	231.34	11.79	29.38	27.28	92.85	2.10	8.40	0.22
3.00	0.25	258.52	231.34	11.75	29.38	27.18	92.51	2.20	8.80	0.22
24.0	21.00	252.69	231.34	9.23	29.38	21.35	72.67	8.03	0.38	0.17
48.0	24.00	241.98	231.34	4.60	29.38	10.64	36.22	18.74	0.78	0.09
72.0	24.00	238.51	231.34	3.10	29.38	7.17	24.40	22.21	0.93	0.06
96.0	24.00	236.23	231.34	2.11	29.38	4.89	16.64	24.49	1.02	0.04
120.0	24.00	235.11	231.34	1.63	29.38	3.77	12.83	25.61	1.07	0.03
144.0	24.00	231.34	231.34	0.00	29.38	0.00	0.00	29.38	1.22	0.00
168.0	24.00	231.34	231.34	0.00	29.38	0.00	0.00	29.38	1.22	0.00

Shaded measurements were taken after sample was placed in the oven.

Appendix H: Drying rate – NORMAL 29/88

Drying Measurements for Sample D3

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight, W_d (g)	Residual water content, Q_i (%)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y (%)	Difference in moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
0.00	0.00	258.31	229.54	12.53	28.77	28.77	100.00	0.00	0.00	0.23
0.08	0.08	258.15	229.54	12.46	28.77	28.61	99.44	0.16	2.00	0.23
0.17	0.09	258.03	229.54	12.41	28.77	28.49	99.03	0.28	3.11	0.23
0.25	0.08	257.93	229.54	12.37	28.77	28.39	98.68	0.38	4.75	0.23
0.33	0.08	257.82	229.54	12.32	28.77	28.28	98.30	0.49	6.13	0.23
0.42	0.09	257.69	229.54	12.26	28.77	28.15	97.84	0.62	6.89	0.23
0.50	0.08	257.59	229.54	12.22	28.77	28.05	97.50	0.72	9.00	0.22
0.58	0.08	257.50	229.54	12.18	28.77	27.96	97.18	0.81	10.13	0.22
0.67	0.09	257.41	229.54	12.14	28.77	27.87	96.87	0.90	10.00	0.22
0.75	0.08	257.34	229.54	12.11	28.77	27.80	96.63	0.97	12.13	0.22
0.83	0.08	257.27	229.54	12.08	28.77	27.73	96.39	1.04	13.00	0.22
0.92	0.09	257.16	229.54	12.03	28.77	27.62	96.00	1.15	12.78	0.22
1.00	0.08	257.07	229.54	11.99	28.77	27.53	95.69	1.24	15.50	0.22
1.25	0.25	256.92	229.54	11.93	28.77	27.38	95.17	1.39	5.56	0.22
1.50	0.25	256.78	229.54	11.87	28.77	27.24	94.68	1.53	6.12	0.22
1.75	0.25	256.64	229.54	11.81	28.77	27.10	94.20	1.67	6.68	0.22
2.00	0.25	256.52	229.54	11.75	28.77	26.98	93.78	1.79	7.16	0.22

Appendix H: Drying rate – NORMAL 29/88

Drying Measurements for Sample D3 (continued)

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight, W_d (g)	Residual water content, Q_i (%)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y (%)	Difference in moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
2.25	0.25	256.41	229.54	11.71	28.77	26.87	93.40	1.90	7.60	0.21
2.50	0.25	256.31	229.54	11.66	28.77	26.77	93.05	2.00	8.00	0.21
2.75	0.25	256.21	229.54	11.62	28.77	26.67	92.70	2.10	8.40	0.21
3.00	0.25	256.10	229.54	11.57	28.77	26.56	92.32	2.21	8.84	0.21
24.0	21.00	251.97	229.54	9.77	28.77	22.43	77.96	6.34	0.30	0.18
48.0	24.00	242.41	229.54	5.61	28.77	12.87	44.73	15.90	0.66	0.10
72.0	24.00	238.69	229.54	3.99	28.77	9.15	31.80	19.62	0.82	0.07
96.0	24.00	235.77	229.54	2.71	28.77	6.23	21.65	22.54	0.94	0.05
120.0	24.00	234.26	229.54	2.06	28.77	4.72	16.41	24.05	1.00	0.04
144.0	24.00	229.54	229.54	0.00	28.77	0.00	0.00	28.77	1.20	0.00
168.0	24.00	229.54	229.54	0.00	28.77	0.00	0.00	28.77	1.20	0.00

Shaded measurements were taken after sample was placed in the oven.

APPENDIX H: DRYING RATE – NORMAL 29/88

DRYING MEASUREMENTS FOR SAMPLE E1

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight, W_d (g)	Residual water content, Q_i (%)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y (%)	Difference in moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
0.00	0.00	249.30	219.41	13.62	29.89	29.89	100.00	0.00	0.00	0.24
0.08	0.08	249.05	219.41	13.51	29.89	29.64	99.16	0.25	3.13	0.24
0.17	0.09	248.90	219.41	13.44	29.89	29.49	98.66	0.40	4.44	0.24
0.25	0.08	248.81	219.41	13.40	29.89	29.40	98.36	0.49	6.13	0.24
0.33	0.08	248.72	219.41	13.36	29.89	29.31	98.06	0.58	7.25	0.23
0.42	0.09	248.59	219.41	13.30	29.89	29.18	97.62	0.71	7.89	0.23
0.50	0.08	248.51	219.41	13.26	29.89	29.10	97.36	0.79	9.88	0.23
0.58	0.08	248.42	219.41	13.22	29.89	29.01	97.06	0.88	11.00	0.23
0.67	0.09	248.33	219.41	13.18	29.89	28.92	96.75	0.97	10.78	0.23
0.75	0.08	248.25	219.41	13.14	29.89	28.84	96.49	1.05	13.13	0.23
0.83	0.08	248.17	219.41	13.11	29.89	28.76	96.22	1.13	14.13	0.23
0.92	0.09	248.09	219.41	13.07	29.89	28.68	95.95	1.21	13.44	0.23
1.00	0.08	248.01	219.41	13.03	29.89	28.60	95.68	1.29	16.13	0.23
1.25	0.25	247.80	219.41	12.94	29.89	28.39	94.98	1.50	6.00	0.23
1.50	0.25	247.64	219.41	12.87	29.89	28.23	94.45	1.66	6.64	0.23
1.75	0.25	247.48	219.41	12.79	29.89	28.07	93.91	1.82	7.28	0.22
2.00	0.25	247.33	219.41	12.73	29.89	27.92	93.41	1.97	7.88	0.22

APPENDIX H: DRYING RATE – NORMAL 29/88

DRYING MEASUREMENTS FOR SAMPLE E1 (CONTINUED)

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight, W_d (g)	Residual water content, Q_i (%)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y (%)	Difference in moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
2.25	0.25	247.20	219.41	12.67	29.89	27.79	92.97	2.10	8.40	0.22
2.50	0.25	247.06	219.41	12.60	29.89	27.65	92.51	2.24	8.96	0.22
2.75	0.25	246.93	219.41	12.54	29.89	27.52	92.07	2.37	9.48	0.22
3.00	0.25	246.77	219.41	12.47	29.89	27.36	91.54	2.53	10.12	0.22
24.0	21.00	237.47	219.41	8.23	29.89	18.06	60.42	11.83	0.56	0.14
48.0	24.00	231.18	219.41	5.36	29.89	11.77	39.38	18.12	0.76	0.09
72.0	24.00	227.75	219.41	3.80	29.89	8.34	27.90	21.55	0.90	0.07
96.0	24.00	225.48	219.41	2.77	29.89	6.07	20.31	23.82	0.99	0.05
120.0	24.00	224.36	219.41	2.26	29.89	4.95	16.56	24.94	1.04	0.04
144.0	24.00	219.41	219.41	0.00	29.89	0.00	0.00	29.89	1.25	0.00
168.0	24.00	219.41	219.41	0.00	29.89	0.00	0.00	29.89	1.25	0.00

Shaded measurements were taken after sample was placed in the oven.

Appendix H: Drying rate – NORMAL 29/88

Drying Measurements for Sample E2

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight, W_d (g)	Residual water content, Q_i (%)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y (%)	Difference in moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
0.00	0.00	245.86	215.61	14.03	30.25	30.25	100.00	0.00	0.00	0.24
0.08	0.08	245.76	215.61	13.98	30.25	30.15	99.67	0.10	1.25	0.24
0.17	0.09	245.66	215.61	13.94	30.25	30.05	99.34	0.20	2.22	0.24
0.25	0.08	245.58	215.61	13.90	30.25	29.97	99.07	0.28	3.50	0.24
0.33	0.08	245.48	215.61	13.85	30.25	29.87	98.74	0.38	4.75	0.24
0.42	0.09	245.36	215.61	13.80	30.25	29.75	98.35	0.50	5.56	0.24
0.50	0.08	245.29	215.61	13.77	30.25	29.68	98.12	0.57	7.13	0.24
0.58	0.08	245.22	215.61	13.73	30.25	29.61	97.88	0.64	8.00	0.24
0.67	0.09	245.14	215.61	13.70	30.25	29.53	97.62	0.72	8.00	0.24
0.75	0.08	245.08	215.61	13.67	30.25	29.47	97.42	0.78	9.75	0.24
0.83	0.08	245.02	215.61	13.64	30.25	29.41	97.22	0.84	10.50	0.24
0.92	0.09	244.96	215.61	13.61	30.25	29.35	97.02	0.90	10.00	0.23
1.00	0.08	244.89	215.61	13.58	30.25	29.28	96.79	0.97	12.13	0.23
1.25	0.25	244.77	215.61	13.52	30.25	29.16	96.40	1.09	4.36	0.23
1.50	0.25	244.66	215.61	13.47	30.25	29.05	96.03	1.20	4.80	0.23
1.75	0.25	244.56	215.61	13.43	30.25	28.95	95.70	1.30	5.20	0.23
2.00	0.25	244.45	215.61	13.38	30.25	28.84	95.34	1.41	5.64	0.23

APPENDIX H: DRYING RATE – NORMAL 29/88

DRYING MEASUREMENTS FOR SAMPLE E2 (CONTINUED)

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight, W_d (g)	Residual water content, Q_i (%)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y (%)	Difference in moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
2.25	0.25	244.34	215.61	13.32	30.25	28.73	94.98	1.52	6.08	0.23
2.50	0.25	244.22	215.61	13.27	30.25	28.61	94.58	1.64	6.56	0.23
2.75	0.25	244.11	215.61	13.22	30.25	28.50	94.21	1.75	7.00	0.23
3.00	0.25	244.00	215.61	13.17	30.25	28.39	93.85	1.86	7.44	0.23
24.0	21.00	236.89	215.61	9.87	30.25	21.28	70.35	8.97	0.43	0.17
48.0	24.00	229.75	215.61	6.56	30.25	14.14	46.74	16.11	0.67	0.11
72.0	24.00	226.07	215.61	4.85	30.25	10.46	34.58	19.79	0.82	0.08
96.0	24.00	223.53	215.61	3.67	30.25	7.92	26.18	22.33	0.93	0.06
120.0	24.00	222.03	215.61	2.98	30.25	6.42	21.22	23.83	0.99	0.05
144.0	24.00	215.63	215.61	0.01	30.25	0.02	0.07	30.23	1.26	0.00
168.0	24.00	215.61	215.61	0.00	30.25	0.00	0.00	30.25	1.26	0.00

Shaded measurements were taken after sample was placed in the oven.

Appendix H: Drying rate – NORMAL 29/88

Drying Measurements for Sample E3

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight, W_d (g)	Residual water content, Q_i (%)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y (%)	Difference in moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
0.00	0.00	252.34	222.92	13.20	29.42	29.42	100.00	0.00	0.00	0.24
0.08	0.08	252.24	222.92	13.15	29.42	29.32	99.66	0.10	1.25	0.23
0.17	0.09	252.19	222.92	13.13	29.42	29.27	99.49	0.15	1.67	0.23
0.25	0.08	252.14	222.92	13.11	29.42	29.22	99.32	0.20	2.50	0.23
0.33	0.08	252.08	222.92	13.08	29.42	29.16	99.12	0.26	3.25	0.23
0.42	0.09	251.99	222.92	13.04	29.42	29.07	98.81	0.35	3.89	0.23
0.50	0.08	251.94	222.92	13.02	29.42	29.02	98.64	0.40	5.00	0.23
0.58	0.08	251.88	222.92	12.99	29.42	28.96	98.44	0.46	5.75	0.23
0.67	0.09	251.80	222.92	12.96	29.42	28.88	98.16	0.54	6.00	0.23
0.75	0.08	251.75	222.92	12.93	29.42	28.83	97.99	0.59	7.38	0.23
0.83	0.08	251.69	222.92	12.91	29.42	28.77	97.79	0.65	8.13	0.23
0.92	0.09	251.64	222.92	12.88	29.42	28.72	97.62	0.70	7.78	0.23
1.00	0.08	251.58	222.92	12.86	29.42	28.66	97.42	0.76	9.50	0.23
1.25	0.25	251.47	222.92	12.81	29.42	28.55	97.04	0.87	3.48	0.23
1.50	0.25	251.37	222.92	12.76	29.42	28.45	96.70	0.97	3.88	0.23
1.75	0.25	251.25	222.92	12.71	29.42	28.33	96.30	1.09	4.36	0.23
2.00	0.25	251.14	222.92	12.66	29.42	28.22	95.92	1.20	4.80	0.23

DRYING MEASUREMENTS FOR SAMPLE E3 (CONTINUED)

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight, W_d (g)	Residual water content, Q_i (%)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y (%)	Difference in moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
2.25	0.25	251.04	222.92	12.61	29.42	28.12	95.58	1.30	5.20	0.22
2.50	0.25	250.93	222.92	12.57	29.42	28.01	95.21	1.41	5.64	0.22
2.75	0.25	250.85	222.92	12.53	29.42	27.93	94.94	1.49	5.96	0.22
3.00	0.25	250.73	222.92	12.48	29.42	27.81	94.53	1.61	6.44	0.22
24.0	21.00	243.89	222.92	9.41	29.42	20.97	71.28	8.45	0.40	0.17
48.0	24.00	238.47	222.92	6.98	29.42	15.55	52.86	13.87	0.58	0.12
72.0	24.00	234.24	222.92	5.08	29.42	11.32	38.48	18.10	0.75	0.09
96.0	24.00	231.47	222.92	3.84	29.42	8.55	29.06	20.87	0.87	0.07
120.0	24.00	229.92	222.92	3.14	29.42	7.00	23.79	22.42	0.93	0.06
144.0	24.00	222.93	222.92	0.00	29.42	0.01	0.03	29.41	1.23	0.00
168.0	24.00	222.92	222.92	0.00	29.42	0.00	0.00	29.42	1.23	0.00

Shaded measurements were taken after sample was placed in the oven.

APPENDIX H: DRYING RATE – NORMAL 29/88

DRYING MEASUREMENTS FOR SAMPLE F1

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight, W_d (g)	Residual water content, Q_i (%)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y (%)	Difference in moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
0.00	0.00	254.70	224.22	13.59	30.48	30.48	100.00	0.00	0.00	0.24
0.08	0.08	254.55	224.22	13.53	30.48	30.33	99.51	0.15	1.87	0.24
0.17	0.09	254.45	224.22	13.48	30.48	30.23	99.18	0.25	2.78	0.24
0.25	0.08	254.35	224.22	13.44	30.48	30.13	98.85	0.35	4.37	0.24
0.33	0.08	254.27	224.22	13.40	30.48	30.05	98.59	0.43	5.37	0.24
0.42	0.09	254.17	224.22	13.36	30.48	29.95	98.26	0.53	5.89	0.24
0.50	0.08	254.07	224.22	13.31	30.48	29.85	97.93	0.63	7.87	0.24
0.58	0.08	253.98	224.22	13.27	30.48	29.76	97.64	0.72	9.00	0.24
0.67	0.09	253.91	224.22	13.24	30.48	29.69	97.41	0.79	8.78	0.24
0.75	0.08	253.83	224.22	13.21	30.48	29.61	97.15	0.87	10.87	0.24
0.83	0.08	253.76	224.22	13.17	30.48	29.54	96.92	0.94	11.75	0.24
0.92	0.09	253.68	224.22	13.14	30.48	29.46	96.65	1.02	11.33	0.24
1.00	0.08	253.62	224.22	13.11	30.48	29.40	96.46	1.08	13.50	0.24
1.25	0.25	253.51	224.22	13.06	30.48	29.29	96.10	1.19	4.76	0.23
1.50	0.25	253.37	224.22	13.00	30.48	29.15	95.64	1.33	5.32	0.23
1.75	0.25	253.15	224.22	12.90	30.48	28.93	94.91	1.55	6.20	0.23
2.00	0.25	253.07	224.22	12.87	30.48	28.85	94.65	1.63	6.52	0.23

APPENDIX H: DRYING RATE – NORMAL 29/88

DRYING MEASUREMENTS FOR SAMPLE F1 (CONTINUED)

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight, W_d (g)	Residual water content, Q_i (%)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y (%)	Difference in moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
2.25	0.25	252.89	224.22	12.79	30.48	28.67	94.06	1.81	7.24	0.23
2.50	0.25	252.81	224.22	12.75	30.48	28.59	93.80	1.89	7.56	0.23
2.75	0.25	252.68	224.22	12.69	30.48	28.46	93.37	2.02	8.08	0.23
3.00	0.25	252.58	224.22	12.65	30.48	28.36	93.04	2.12	8.48	0.23
24.0	21.00	242.29	224.22	8.06	30.48	18.07	59.28	12.41	0.59	0.14
48.0	24.00	237.29	224.22	5.83	30.48	13.07	42.88	17.41	0.73	0.10
72.0	24.00	232.70	224.22	3.78	30.48	8.48	27.82	22.00	0.92	0.07
96.0	24.00	230.63	224.22	2.86	30.48	6.41	21.03	24.07	1.00	0.05
120.0	24.00	229.58	224.22	2.39	30.48	5.36	17.59	25.12	1.05	0.04
144.0	24.00	224.24	224.22	0.01	30.48	0.02	0.07	30.46	1.27	0.00
168.0	24.00	224.22	224.22	0.00	30.48	0.00	0.00	30.48	1.27	0.00

Shaded measurements were taken after sample was placed in the oven.

APPENDIX H: DRYING RATE – NORMAL 29/88

DRYING MEASUREMENTS FOR SAMPLE F2

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight, W_d (g)	Residual water content, Q_i (%)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y (%)	Difference in moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
0.00	0.00	261.21	230.99	13.08	30.22	30.22	100.00	0.00	0.00	0.24
0.08	0.08	261.10	230.99	13.04	30.22	30.11	99.64	0.11	1.37	0.24
0.17	0.09	261.03	230.99	13.00	30.22	30.04	99.40	0.18	2.00	0.24
0.25	0.08	260.95	230.99	12.97	30.22	29.96	99.14	0.26	3.25	0.24
0.33	0.08	260.87	230.99	12.94	30.22	29.88	98.87	0.34	4.25	0.24
0.42	0.09	260.80	230.99	12.91	30.22	29.81	98.64	0.41	4.56	0.24
0.50	0.08	260.71	230.99	12.87	30.22	29.72	98.35	0.50	6.25	0.24
0.58	0.08	260.64	230.99	12.84	30.22	29.65	98.11	0.57	7.12	0.24
0.67	0.09	260.58	230.99	12.81	30.22	29.59	97.92	0.63	7.00	0.24
0.75	0.08	260.50	230.99	12.78	30.22	29.51	97.65	0.71	8.87	0.24
0.83	0.08	260.45	230.99	12.75	30.22	29.46	97.49	0.76	9.50	0.24
0.92	0.09	260.38	230.99	12.72	30.22	29.39	97.25	0.83	9.22	0.24
1.00	0.08	260.32	230.99	12.70	30.22	29.33	97.05	0.89	11.12	0.23
1.25	0.25	260.22	230.99	12.65	30.22	29.23	96.72	0.99	3.96	0.23
1.50	0.25	260.11	230.99	12.61	30.22	29.12	96.36	1.10	4.40	0.23
1.75	0.25	259.99	230.99	12.55	30.22	29.00	95.96	1.22	4.88	0.23
2.00	0.25	259.89	230.99	12.51	30.22	28.90	95.63	1.32	5.28	0.23

APPENDIX H: DRYING RATE – NORMAL 29/88

DRYING MEASUREMENTS FOR SAMPLE F2 (CONTINUED)

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight, W_d (g)	Residual water content, Q_i (%)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y (%)	Difference in moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
2.25	0.25	259.78	230.99	12.46	30.22	28.79	95.27	1.43	5.72	0.23
2.50	0.25	259.66	230.99	12.41	30.22	28.67	94.87	1.55	6.20	0.23
2.75	0.25	259.54	230.99	12.36	30.22	28.55	94.47	1.67	6.68	0.23
3.00	0.25	259.43	230.99	12.31	30.22	28.44	94.11	1.78	7.12	0.23
24.0	21.00	253.63	230.99	9.80	30.22	22.64	74.92	7.58	0.36	0.18
48.0	24.00	245.87	230.99	6.44	30.22	14.88	49.24	15.34	0.64	0.12
72.0	24.00	241.21	230.99	4.42	30.22	10.22	33.82	20.00	0.83	0.08
96.0	24.00	238.84	230.99	3.40	30.22	7.85	25.98	22.37	0.93	0.06
120.0	24.00	237.80	230.99	2.95	30.22	6.81	22.53	23.41	0.98	0.05
144.0	24.00	230.99	230.99	0.00	30.22	0.00	0.00	30.22	1.26	0.00
168.0	24.00	230.99	230.99	0.00	30.22	0.00	0.00	30.22	1.26	0.00

Shaded measurements were taken after sample was placed in the oven.

APPENDIX H: DRYING RATE – NORMAL 29/88

DRYING MEASUREMENTS FOR SAMPLE F3

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight, W_d (g)	Residual water content, Q_i (%)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y (%)	Difference in moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
0.00	0.00	264.96	232.56	13.93	32.40	32.40	100.00	0.00	0.00	0.26
0.08	0.08	264.88	232.56	13.90	32.40	32.32	99.75	0.08	1.00	0.26
0.17	0.09	264.81	232.56	13.87	32.40	32.25	99.54	0.15	1.67	0.26
0.25	0.08	264.75	232.56	13.84	32.40	32.19	99.35	0.21	2.62	0.26
0.33	0.08	264.67	232.56	13.81	32.40	32.11	99.10	0.29	3.62	0.26
0.42	0.09	264.61	232.56	13.78	32.40	32.05	98.92	0.35	3.89	0.26
0.50	0.08	264.53	232.56	13.75	32.40	31.97	98.67	0.43	5.38	0.26
0.58	0.08	264.46	232.56	13.72	32.40	31.90	98.46	0.50	6.25	0.26
0.67	0.09	264.40	232.56	13.69	32.40	31.84	98.27	0.56	6.22	0.25
0.75	0.08	264.32	232.56	13.66	32.40	31.76	98.02	0.64	8.00	0.25
0.83	0.08	264.26	232.56	13.63	32.40	31.70	97.84	0.70	8.75	0.25
0.92	0.09	264.19	232.56	13.60	32.40	31.63	97.62	0.77	8.56	0.25
1.00	0.08	264.13	232.56	13.57	32.40	31.57	97.44	0.83	10.37	0.25
1.25	0.25	264.04	232.56	13.54	32.40	31.48	97.16	0.92	3.68	0.25
1.50	0.25	263.94	232.56	13.49	32.40	31.38	96.85	1.02	4.08	0.25
1.75	0.25	263.84	232.56	13.45	32.40	31.28	96.54	1.12	4.48	0.25
2.00	0.25	263.72	232.56	13.40	32.40	31.16	96.17	1.24	4.96	0.25

Appendix H: Drying rate – NORMAL 29/88

Drying Measurements for Sample F3 (continued)

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight, W_d (g)	Residual water content, Q_i (%)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y (%)	Difference in moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
2.25	0.25	263.61	232.56	13.35	32.40	31.05	95.83	1.35	5.40	0.25
2.50	0.25	263.47	232.56	13.29	32.40	30.91	95.40	1.49	5.96	0.25
2.75	0.25	263.37	232.56	13.25	32.40	30.81	95.09	1.59	6.36	0.25
3.00	0.25	263.23	232.56	13.19	32.40	30.67	94.66	1.73	6.92	0.25
24.0	21.00	258.63	232.56	11.21	32.40	26.07	80.46	6.33	0.30	0.21
48.0	24.00	246.58	232.56	6.03	32.40	14.02	43.27	18.38	0.77	0.11
72.0	24.00	242.66	232.56	4.34	32.40	10.10	31.17	22.30	0.93	0.08
96.0	24.00	240.42	232.56	3.38	32.40	7.86	24.26	24.54	1.02	0.06
120.0	24.00	239.39	232.56	2.94	32.40	6.83	21.08	25.57	1.07	0.05
144.0	24.00	232.56	232.56	0.00	32.40	0.00	0.00	32.40	1.35	0.00
168.0	24.00	232.56	232.56	0.00	32.40	0.00	0.00	32.40	1.35	0.00

Shaded measurements were taken after sample was placed in the oven.

Appendix H: Drying rate – NORMAL 29/88

Drying Measurements for Sample S1

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight, W_d (g)	Residual water content, Q_i (%)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y (%)	Difference in moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
0.00	0.00	318.56	310.04	2.75	8.52	8.52	100.00	0.00	0.00	0.07
0.08	0.08	318.47	310.04	2.72	8.52	8.43	98.94	0.09	1.12	0.07
0.17	0.09	318.44	310.04	2.71	8.52	8.40	98.59	0.12	1.33	0.07
0.25	0.08	318.38	310.04	2.69	8.52	8.34	97.89	0.18	2.25	0.07
0.33	0.08	318.34	310.04	2.68	8.52	8.30	97.42	0.22	2.75	0.07
0.42	0.09	318.29	310.04	2.66	8.52	8.25	96.83	0.27	3.00	0.07
0.50	0.08	318.24	310.04	2.64	8.52	8.20	96.24	0.32	4.00	0.07
0.58	0.08	318.20	310.04	2.63	8.52	8.16	95.77	0.36	4.50	0.07
0.67	0.09	318.15	310.04	2.62	8.52	8.11	95.19	0.41	4.56	0.06
0.75	0.08	318.11	310.04	2.60	8.52	8.07	94.72	0.45	5.62	0.06
0.83	0.08	318.06	310.04	2.59	8.52	8.02	94.13	0.50	6.25	0.06
0.92	0.09	318.02	310.04	2.57	8.52	7.98	93.66	0.54	6.00	0.06
1.00	0.08	317.95	310.04	2.55	8.52	7.91	92.84	0.61	7.63	0.06
1.25	0.25	317.88	310.04	2.53	8.52	7.84	92.02	0.68	2.72	0.06
1.50	0.25	317.74	310.04	2.48	8.52	7.70	90.38	0.82	3.28	0.06
1.75	0.25	317.66	310.04	2.46	8.52	7.62	89.44	0.90	3.60	0.06
2.00	0.25	317.53	310.04	2.42	8.52	7.49	87.91	1.03	4.12	0.06

APPENDIX H: DRYING RATE – NORMAL 29/88

DRYING MEASUREMENTS FOR SAMPLE S1 (CONTINUED)

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight, W_d (g)	Residual water content, Q_i (%)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y (%)	Difference in moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
2.25	0.25	317.43	310.04	2.38	8.52	7.39	86.74	1.13	4.52	0.06
2.50	0.25	317.34	310.04	2.35	8.52	7.30	85.68	1.22	4.88	0.06
2.75	0.25	317.26	310.04	2.33	8.52	7.22	84.74	1.30	5.20	0.06
3.00	0.25	317.18	310.04	2.30	8.52	7.14	83.80	1.38	5.52	0.06
24.0	21.00	312.85	310.04	0.91	8.52	2.81	32.98	5.71	0.27	0.02
48.0	24.00	311.44	310.04	0.45	8.52	1.40	16.43	7.12	0.30	0.01
72.0	24.00	310.92	310.04	0.28	8.52	0.88	10.33	7.64	0.32	0.01
96.0	24.00	310.04	310.04	0.00	8.52	0.00	0.00	8.52	0.35	0.00
120.0	24.00	310.04	310.04	0.00	8.52	0.00	0.00	8.52	0.35	0.00

Shaded measurements were taken after sample was placed in the oven.

Appendix H: Drying rate – NORMAL 29/88

Drying Measurements for Sample S2

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight, W_d (g)	Residual water content, Q_i (%)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y (%)	Difference in moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
0.00	0.00	320.96	312.31	2.77	8.65	8.65	100.00	0.00	0.00	0.07
0.08	0.08	320.90	312.31	2.75	8.65	8.59	99.31	0.06	0.75	0.07
0.17	0.09	320.85	312.31	2.73	8.65	8.54	98.73	0.11	1.22	0.07
0.25	0.08	320.81	312.31	2.72	8.65	8.50	98.27	0.15	1.87	0.07
0.33	0.08	320.77	312.31	2.71	8.65	8.46	97.80	0.19	2.37	0.07
0.42	0.09	320.71	312.31	2.69	8.65	8.40	97.11	0.25	2.78	0.07
0.50	0.08	320.67	312.31	2.68	8.65	8.36	96.65	0.29	3.62	0.07
0.58	0.08	320.62	312.31	2.66	8.65	8.31	96.07	0.34	4.25	0.07
0.67	0.09	320.58	312.31	2.65	8.65	8.27	95.61	0.38	4.22	0.07
0.75	0.08	320.54	312.31	2.64	8.65	8.23	95.14	0.42	5.25	0.07
0.83	0.08	320.50	312.31	2.62	8.65	8.19	94.68	0.46	5.75	0.07
0.92	0.09	320.46	312.31	2.61	8.65	8.15	94.22	0.50	5.56	0.07
1.00	0.08	320.39	312.31	2.59	8.65	8.08	93.41	0.57	7.12	0.06
1.25	0.25	320.30	312.31	2.56	8.65	7.99	92.37	0.66	2.64	0.06
1.50	0.25	320.19	312.31	2.52	8.65	7.88	91.10	0.77	3.08	0.06
1.75	0.25	320.12	312.31	2.50	8.65	7.81	90.29	0.84	3.36	0.06
2.00	0.25	320.01	312.31	2.47	8.65	7.70	89.02	0.95	3.80	0.06

DRYING MEASUREMENTS FOR SAMPLE S2 (CONTINUED)

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight, W_d (g)	Residual water content, Q_i (%)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y (%)	Difference in moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
2.25	0.25	319.91	312.31	2.43	8.65	7.60	87.86	1.05	4.20	0.06
2.50	0.25	319.83	312.31	2.41	8.65	7.52	86.94	1.13	4.52	0.06
2.75	0.25	319.74	312.31	2.38	8.65	7.43	85.90	1.22	4.88	0.06
3.00	0.25	319.67	312.31	2.36	8.65	7.36	85.09	1.29	5.16	0.06
24.0	21.00	315.61	312.31	1.06	8.65	3.30	38.15	5.35	0.25	0.03
48.0	24.00	313.82	312.31	0.48	8.65	1.51	17.46	7.14	0.30	0.01
72.0	24.00	313.26	312.31	0.30	8.65	0.95	10.98	7.70	0.32	0.01
96.0	24.00	312.31	312.31	0.00	8.65	0.00	0.00	8.65	0.36	0.00
120.0	24.00	312.31	312.31	0.00	8.65	0.00	0.00	8.65	0.36	0.00

Shaded measurements were taken after sample was placed in the oven.

Appendix H: Drying rate – NORMAL 29/88

Drying Measurements for Sample S3

Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight, W_d (g)	Residual water content, Q_i (%)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y (%)	Difference in moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
0.00	0.00	331.93	323.49	2.61	8.44	8.44	100.00	0.00	0.00	0.07
0.08	0.08	331.85	323.49	2.58	8.44	8.36	99.05	0.08	1.00	0.07
0.17	0.09	331.80	323.49	2.57	8.44	8.31	98.46	0.13	1.44	0.07
0.25	0.08	331.75	323.49	2.55	8.44	8.26	97.87	0.18	2.25	0.07
0.33	0.08	331.72	323.49	2.54	8.44	8.23	97.51	0.21	2.62	0.07
0.42	0.09	331.66	323.49	2.53	8.44	8.17	96.80	0.27	3.00	0.07
0.50	0.08	331.61	323.49	2.51	8.44	8.12	96.21	0.32	4.00	0.06
0.58	0.08	331.57	323.49	2.50	8.44	8.08	95.73	0.36	4.50	0.06
0.67	0.09	331.52	323.49	2.48	8.44	8.03	95.14	0.41	4.56	0.06
0.75	0.08	331.47	323.49	2.47	8.44	7.98	94.55	0.46	5.75	0.06
0.83	0.08	331.44	323.49	2.46	8.44	7.95	94.19	0.49	6.13	0.06
0.92	0.09	331.36	323.49	2.43	8.44	7.87	93.25	0.57	6.33	0.06
1.00	0.08	331.32	323.49	2.42	8.44	7.83	92.77	0.61	7.63	0.06
1.25	0.25	331.17	323.49	2.37	8.44	7.68	91.00	0.76	3.04	0.06
1.50	0.25	331.11	323.49	2.36	8.44	7.62	90.28	0.82	3.28	0.06
1.75	0.25	330.97	323.49	2.31	8.44	7.48	88.63	0.96	3.84	0.06
2.00	0.25	330.89	323.49	2.29	8.44	7.40	87.68	1.04	4.16	0.06

Appendix H: Drying rate – NORMAL 29/88

Drying Measurements for Sample S3 (continued)

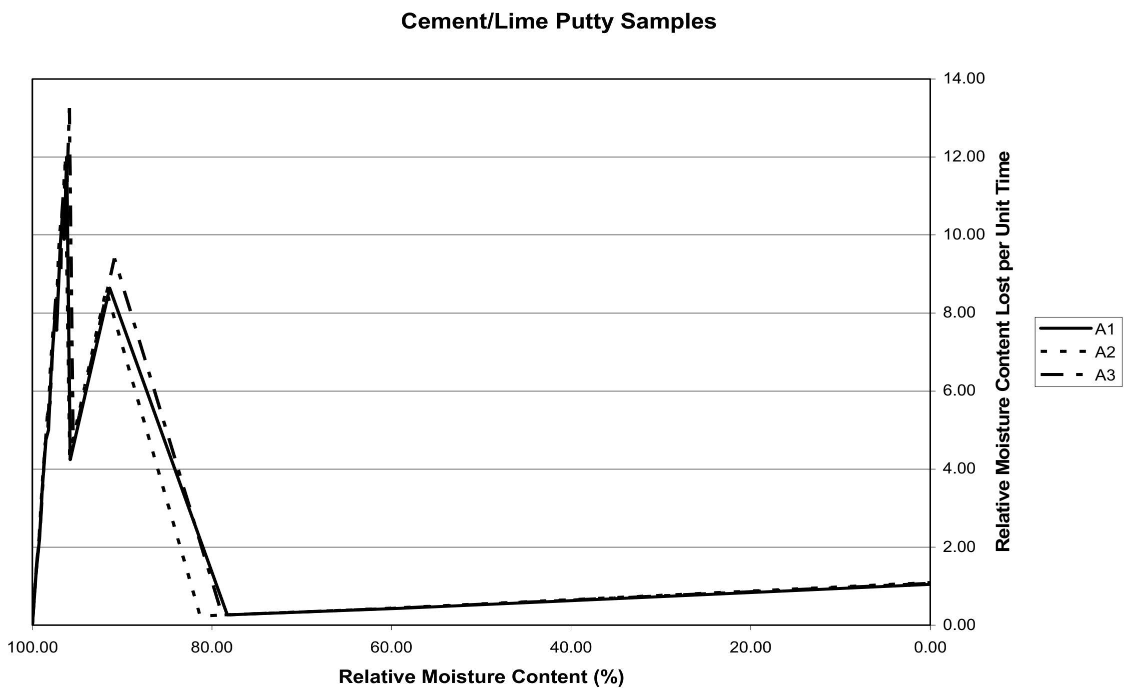
Time (hours)	Time difference, Δt (hours)	Weight, W_t (g)	Dry weight, W_d (g)	Residual water content, Q_i (%)	Initial water content, U_0 (g)	Water content, U_t (g)	Relative moisture content, Y (%)	Difference in moisture content, ΔY	Relative moisture content lost/unit time, $\Delta Y/\Delta t$	Moisture content, Ψ (g/cm^3)
2.25	0.25	330.76	323.49	2.25	8.44	7.27	86.14	1.17	4.68	0.06
2.50	0.25	330.68	323.49	2.22	8.44	7.19	85.19	1.25	5.00	0.06
2.75	0.25	330.57	323.49	2.19	8.44	7.08	83.89	1.36	5.44	0.06
3.00	0.25	330.49	323.49	2.16	8.44	7.00	82.94	1.44	5.76	0.06
24.0	21.00	326.87	323.49	1.04	8.44	3.38	40.05	5.06	0.24	0.03
48.0	24.00	325.05	323.49	0.48	8.44	1.56	18.48	6.88	0.29	0.01
72.0	24.00	324.50	323.49	0.31	8.44	1.01	11.97	7.43	0.31	0.01
96.0	24.00	323.49	323.49	0.00	8.44	0.00	0.00	8.44	0.35	0.00
120.0	24.00	323.49	323.49	0.00	8.44	0.00	0.00	8.44	0.35	0.00

Shaded measurements were taken after sample was placed in the oven.

APPENDIX H: DRYING RATE – NORMAL 29/88

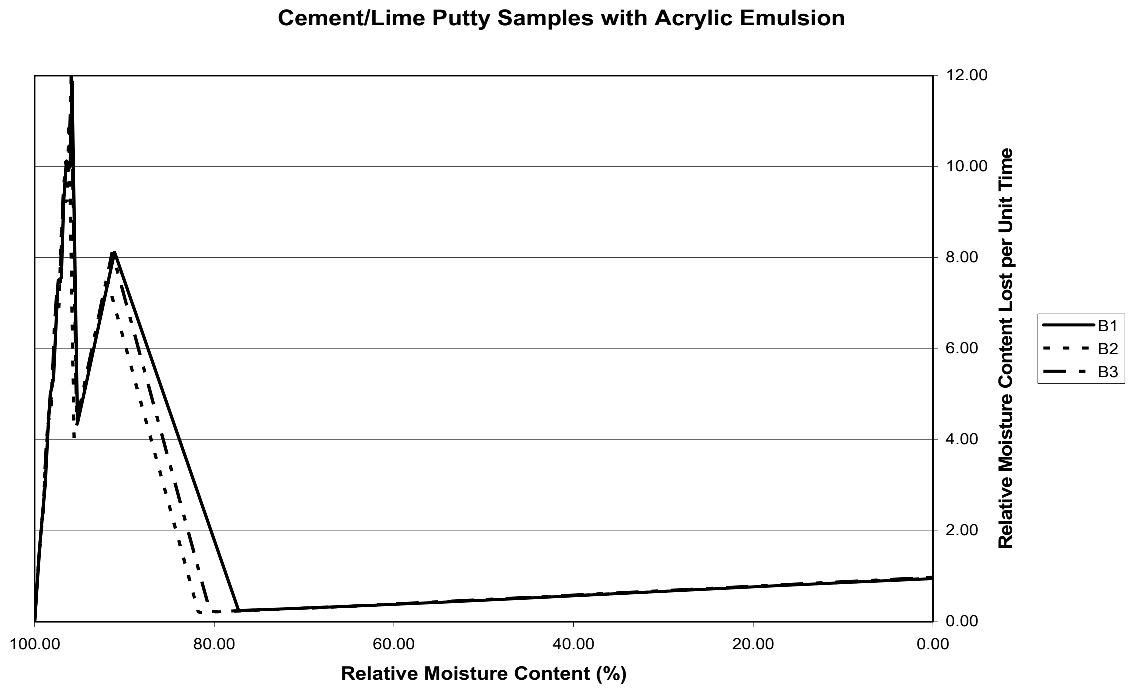
DRYING RATE GRAPHS

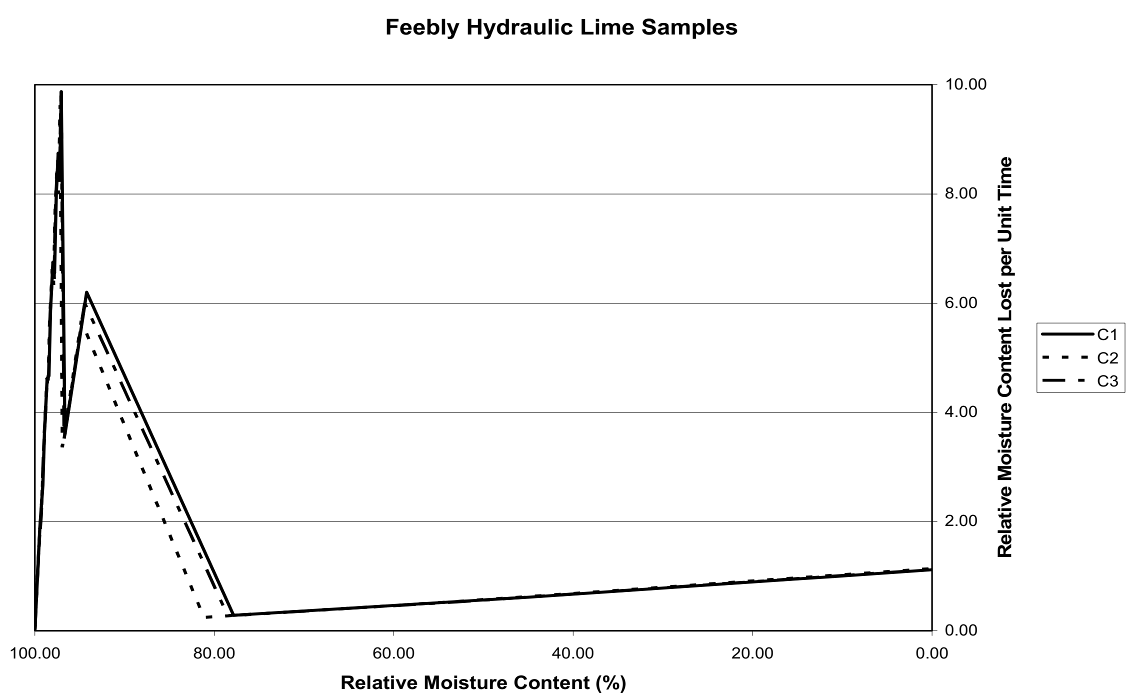
Critical moisture content for all mortar samples and the stone samples was at one hour. Critical moisture content is the point at which the transition from the capillarity of water to the diffusion of water vapor in a material occurs.



APPENDIX H: DRYING RATE – NORMAL 29/88

DRYING RATE GRAPHS

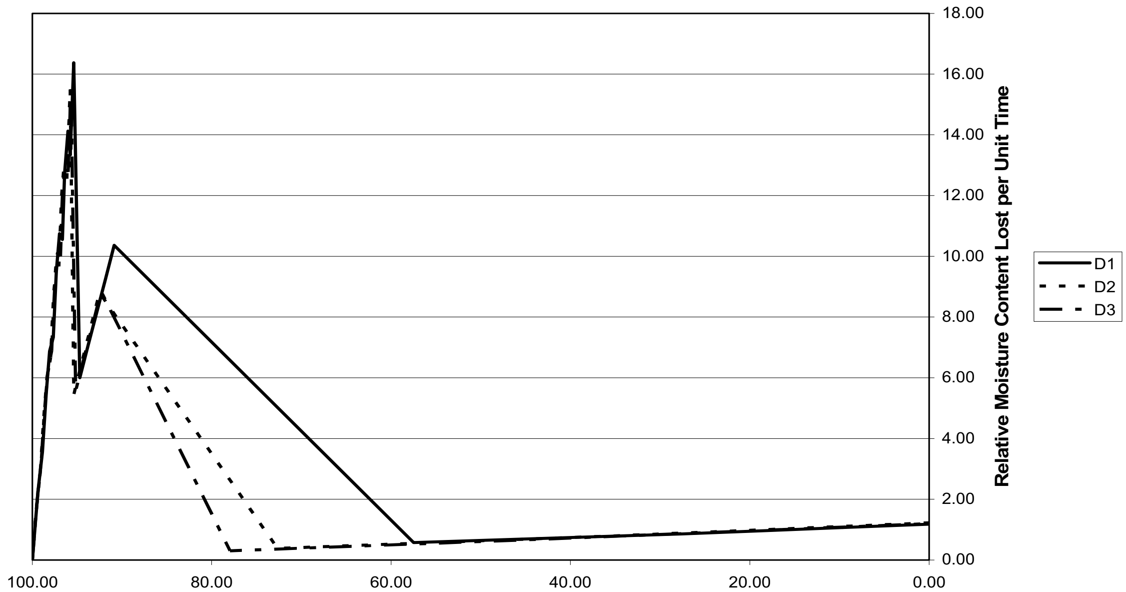




APPENDIX H: DRYING RATE – NORMAL 29/88

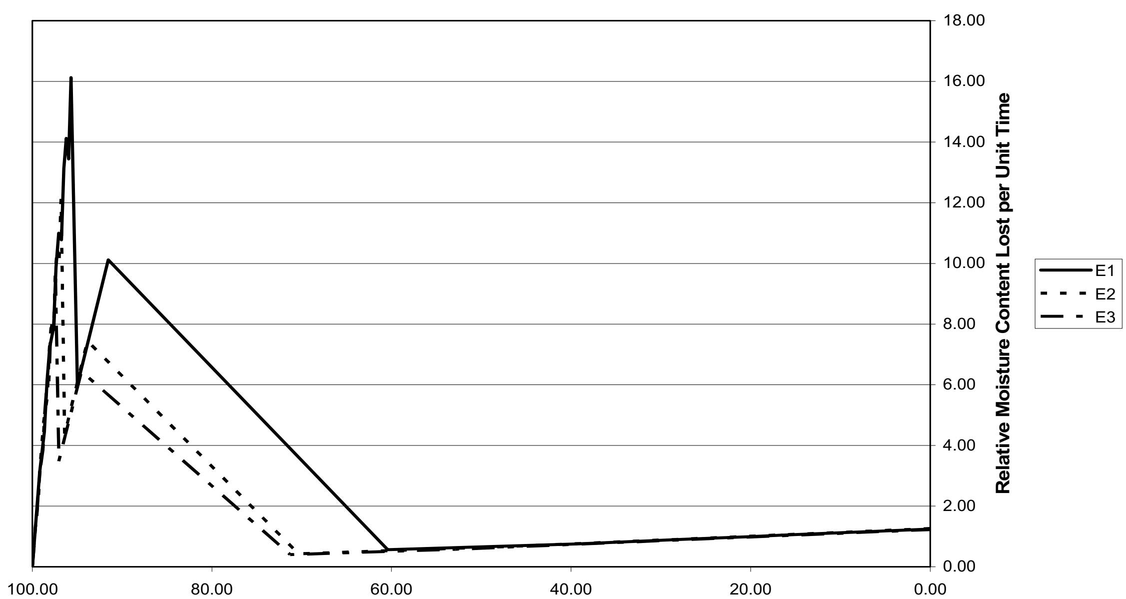
DRYING RATE GRAPHS

Feebly Hydraulic Lime Samples with Acrylic Emulsion



Relative Moisture Content (%)

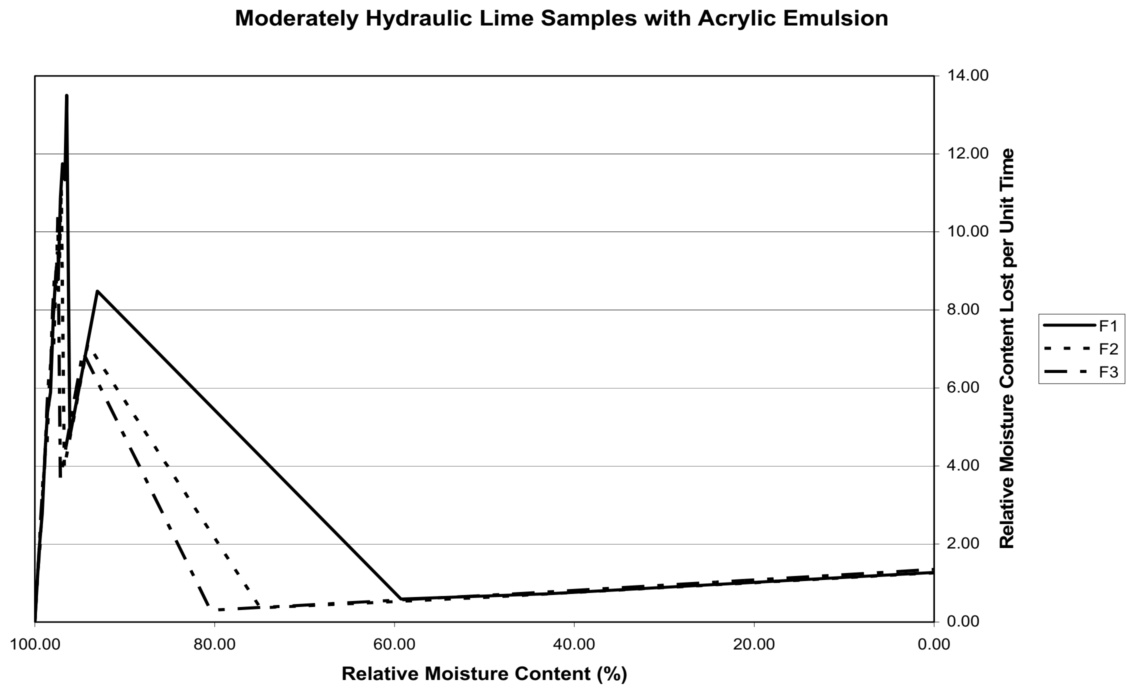
Moderately Hydraulic Lime Samples

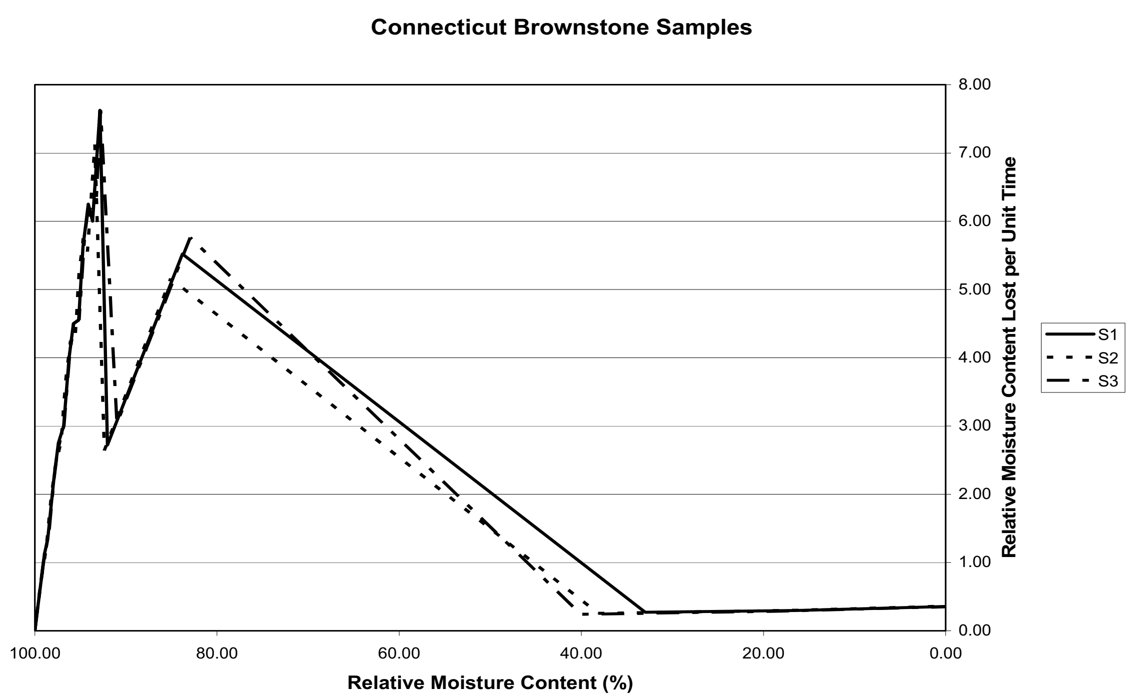


Relative Moisture Content (%)

APPENDIX H: DRYING RATE – NORMAL 29/88

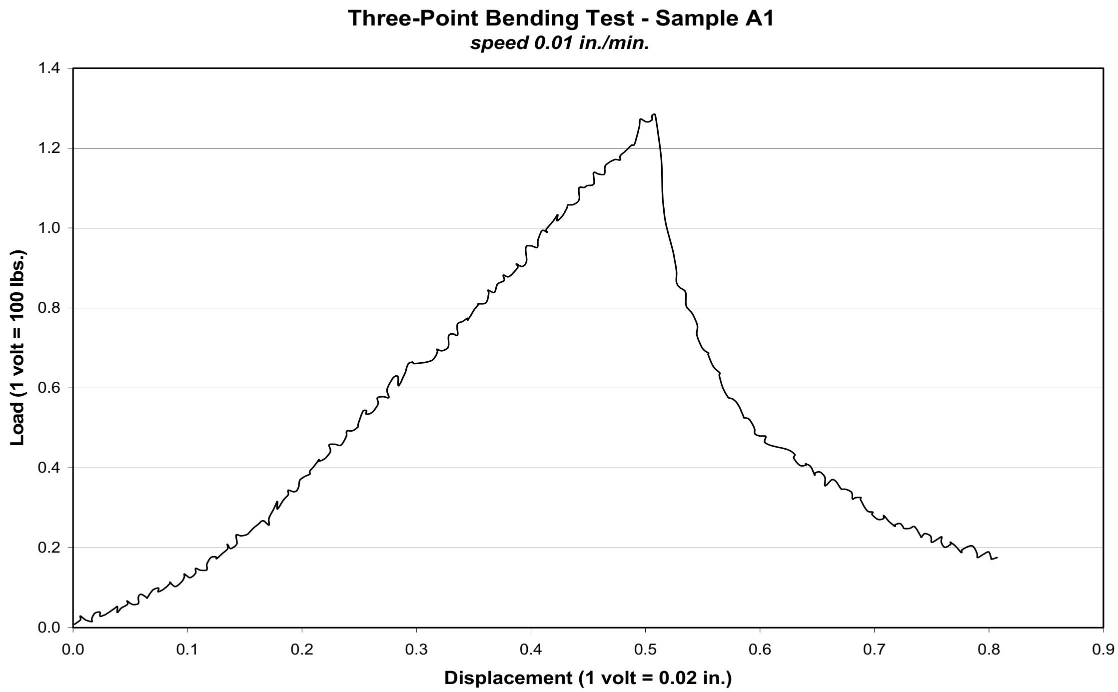
DRYING RATE GRAPHS

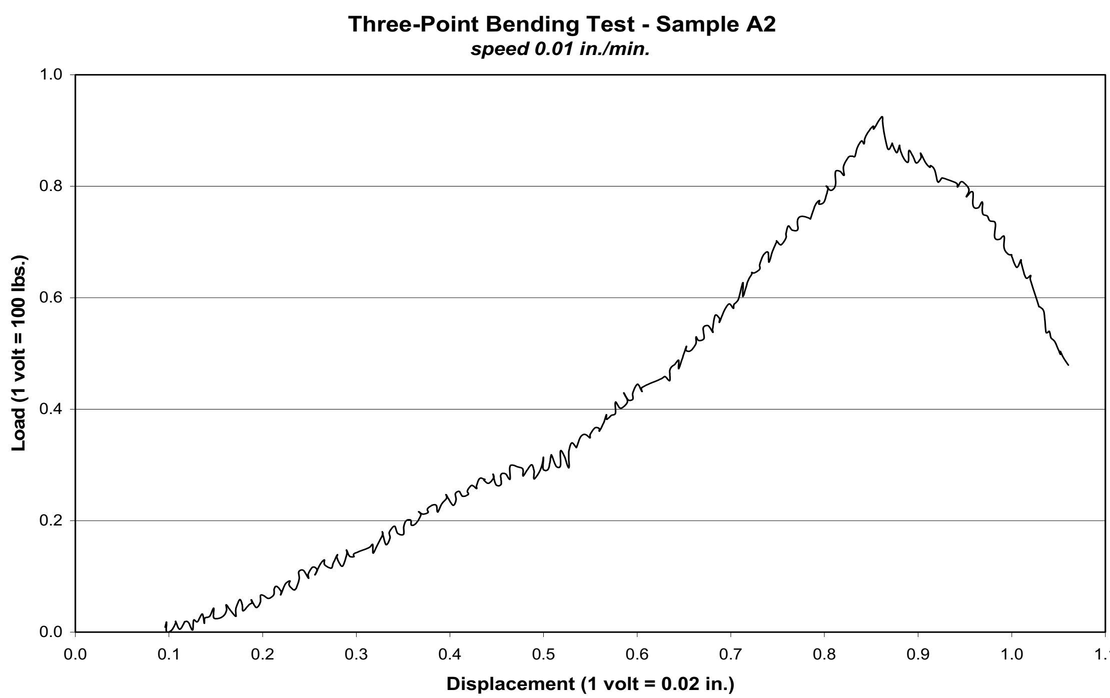




APPENDIX I: FLEXURAL TEST – ASTM C580-98

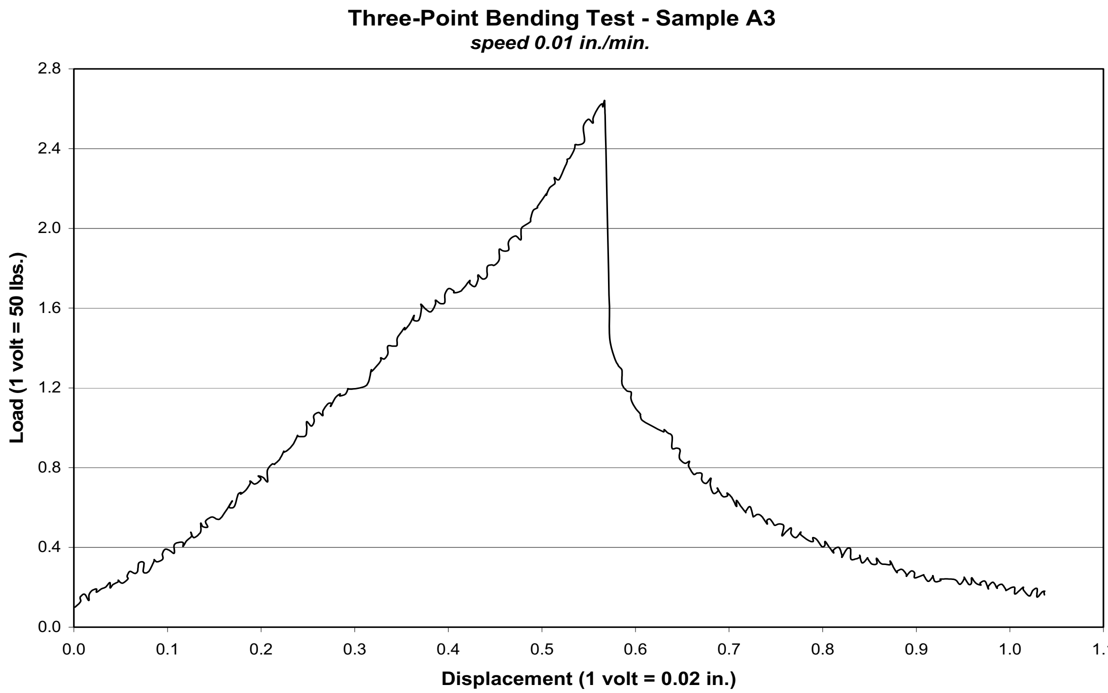
LOAD-DEFLECTION CURVES

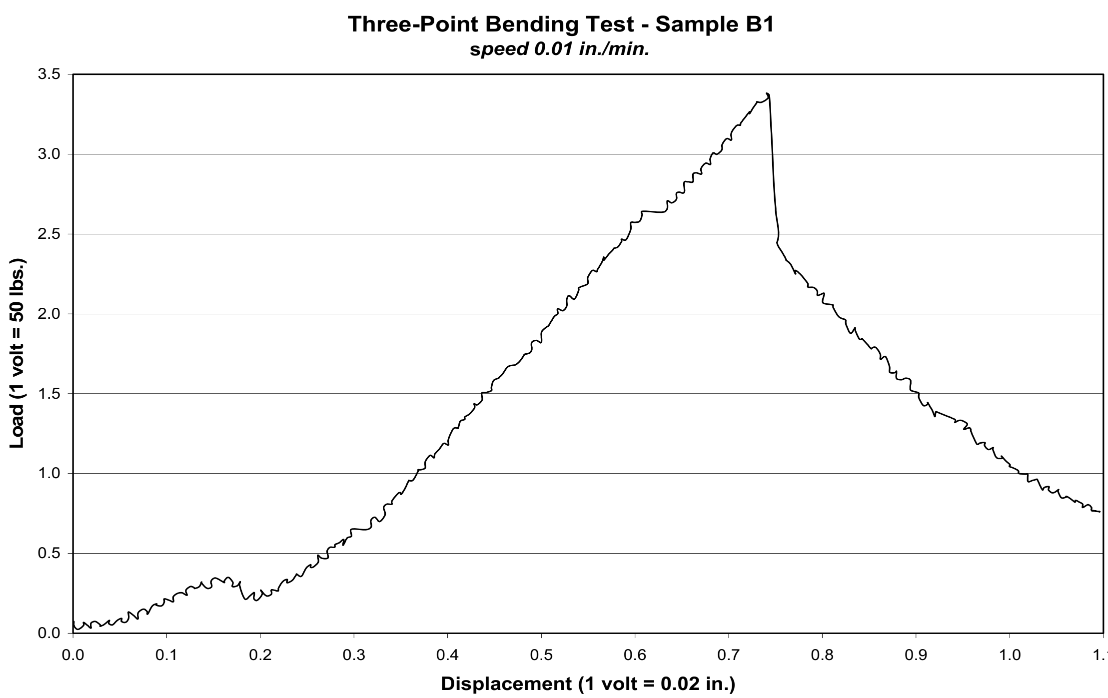




APPENDIX I: FLEXURAL TEST – ASTM C580-98

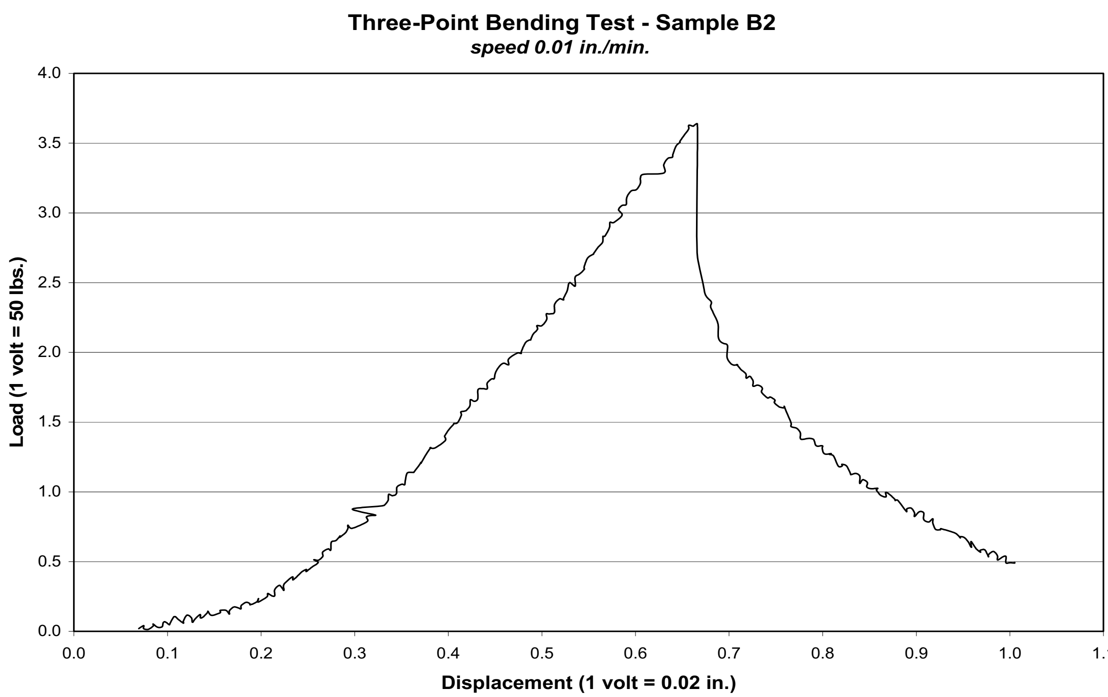
LOAD-DEFLECTION CURVES

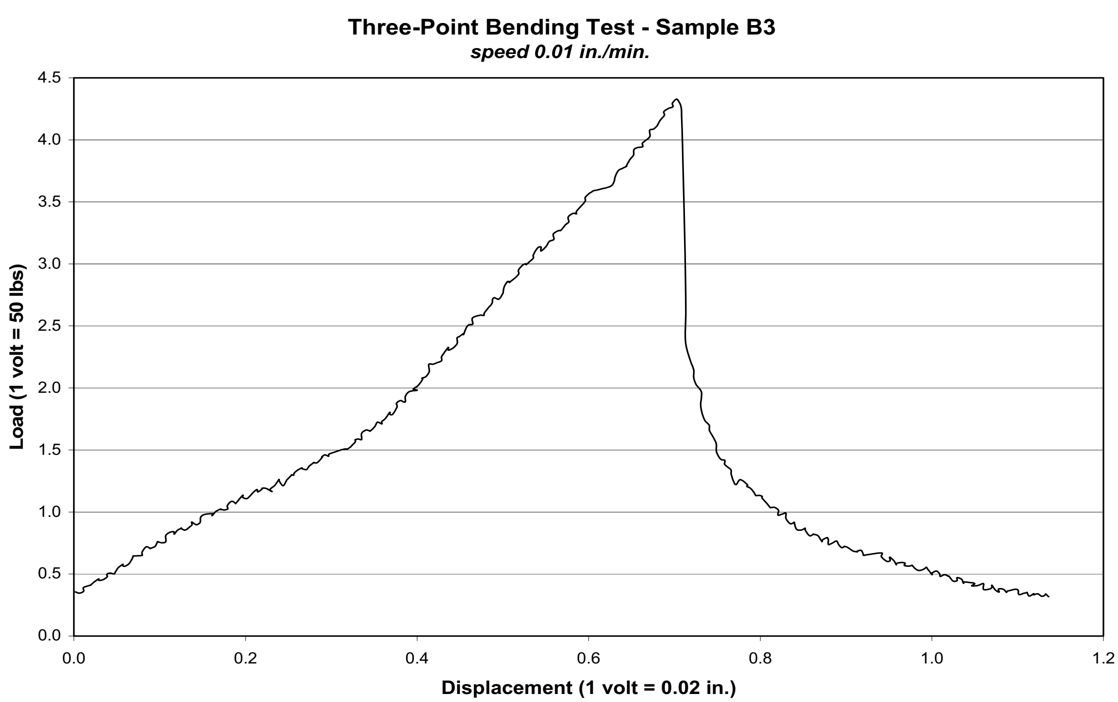




APPENDIX I: FLEXURAL TEST – ASTM C580-98

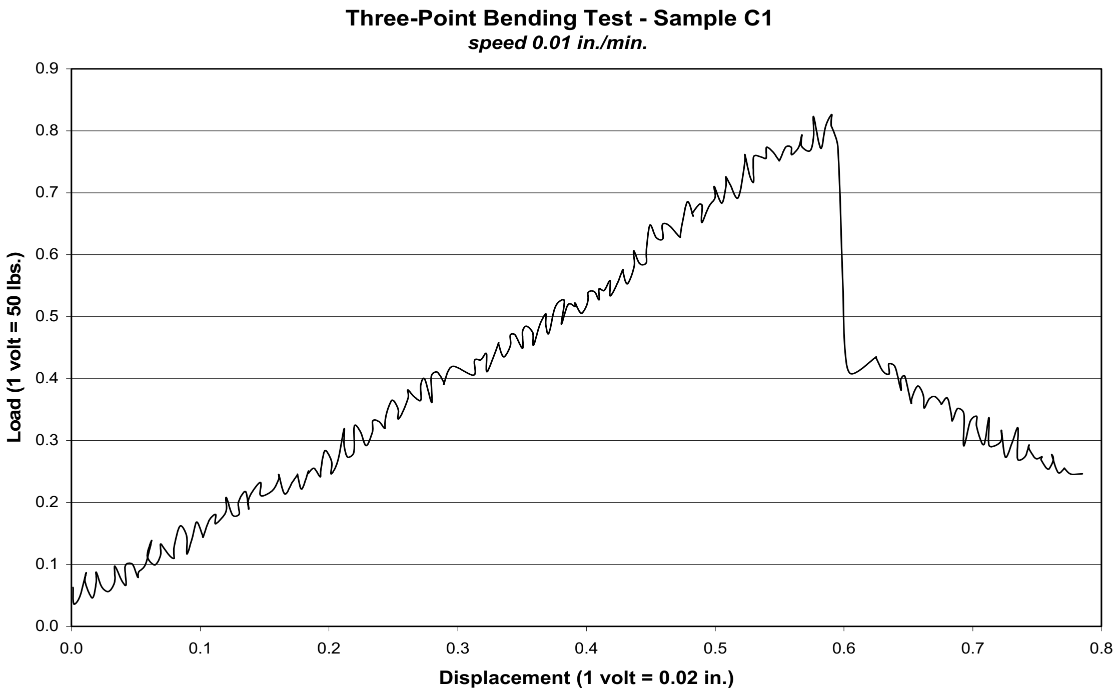
LOAD-DEFLECTION CURVES

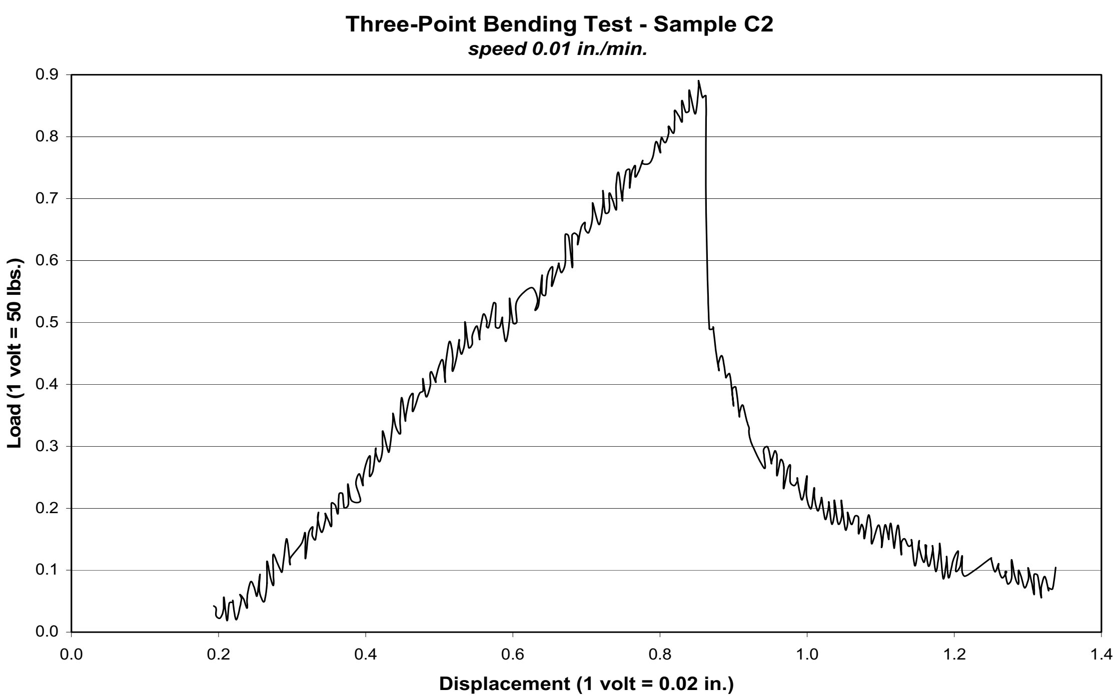




APPENDIX I: FLEXURAL TEST – ASTM C580-98

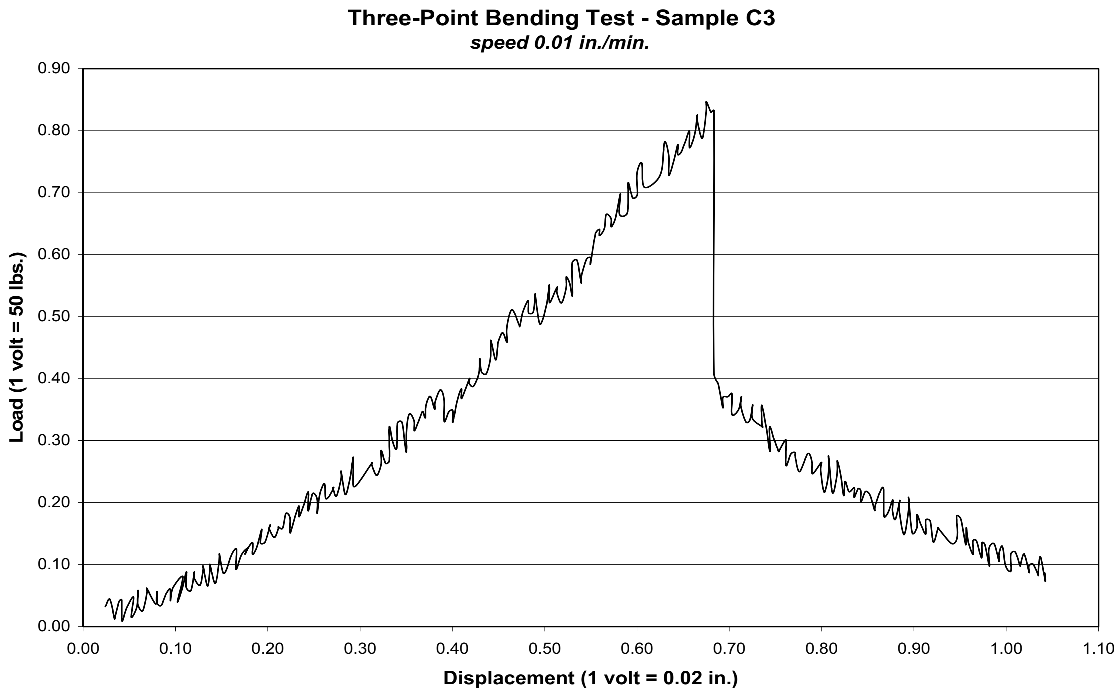
LOAD-DEFLECTION CURVES

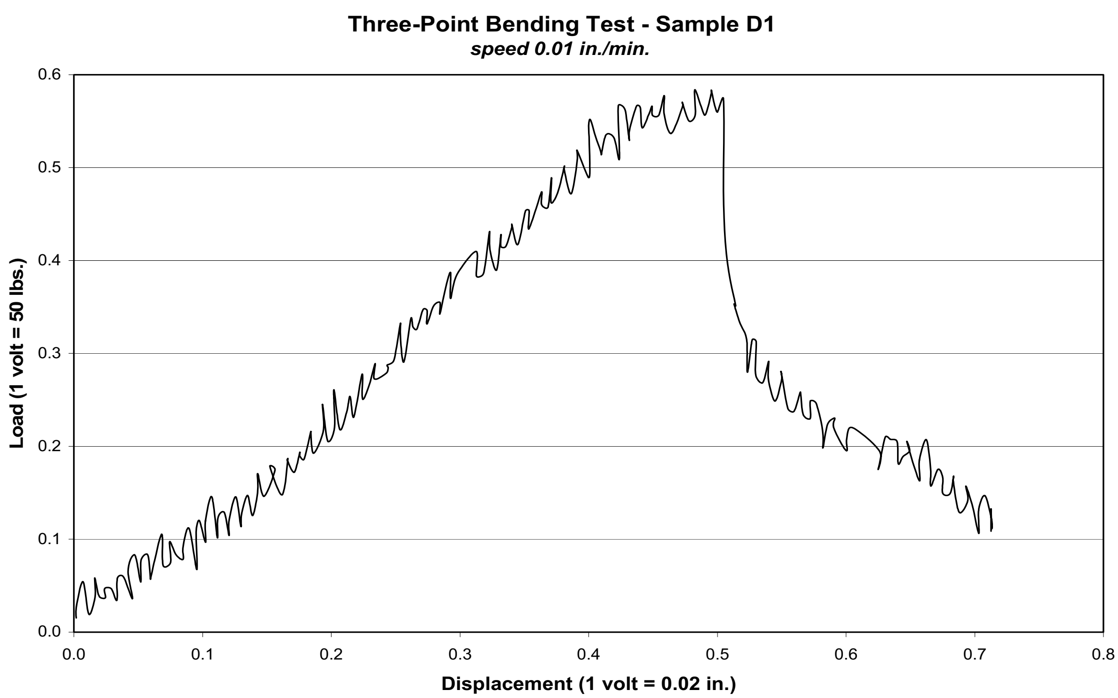




APPENDIX I: FLEXURAL TEST – ASTM C580-98

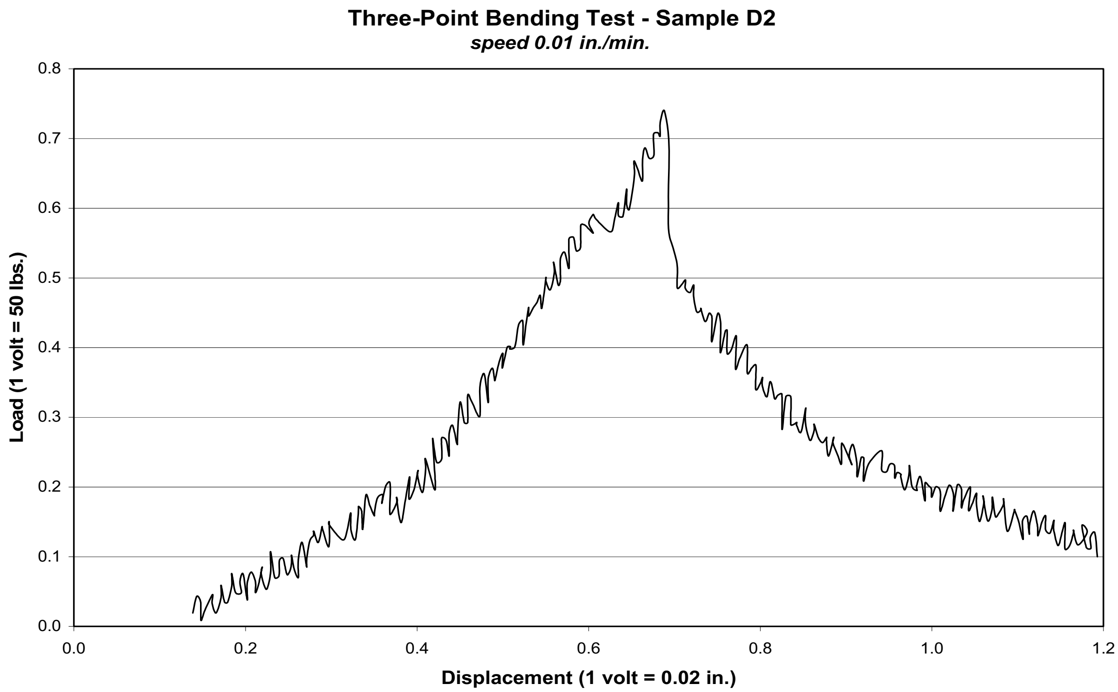
LOAD-DEFLECTION CURVES

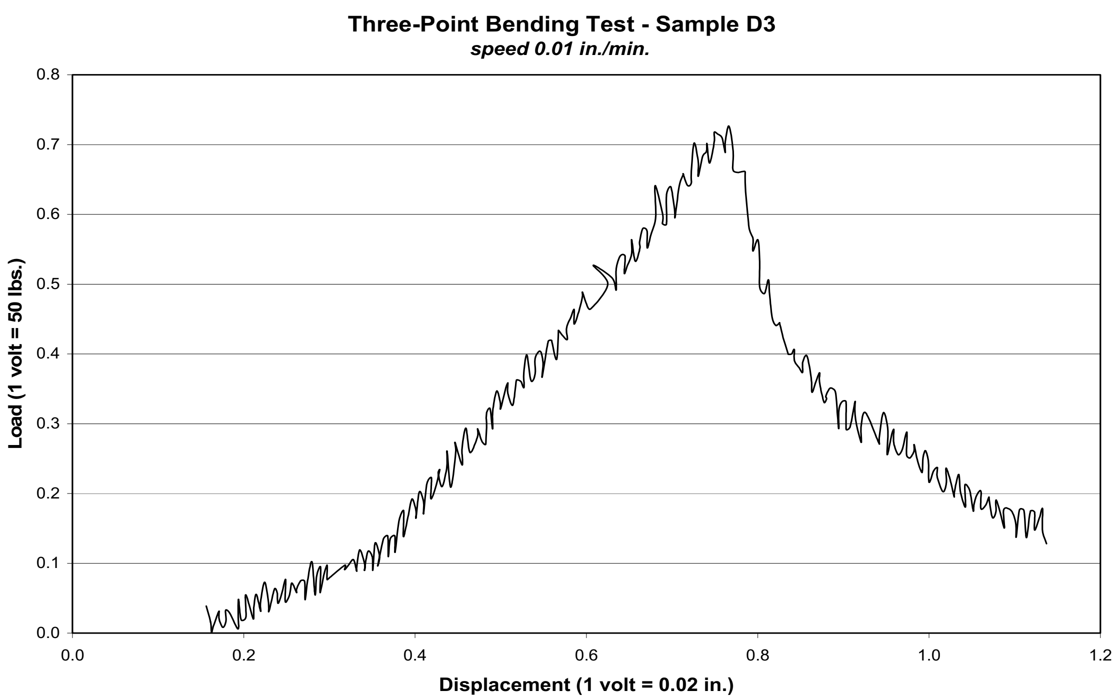




APPENDIX I: FLEXURAL TEST – ASTM C580-98

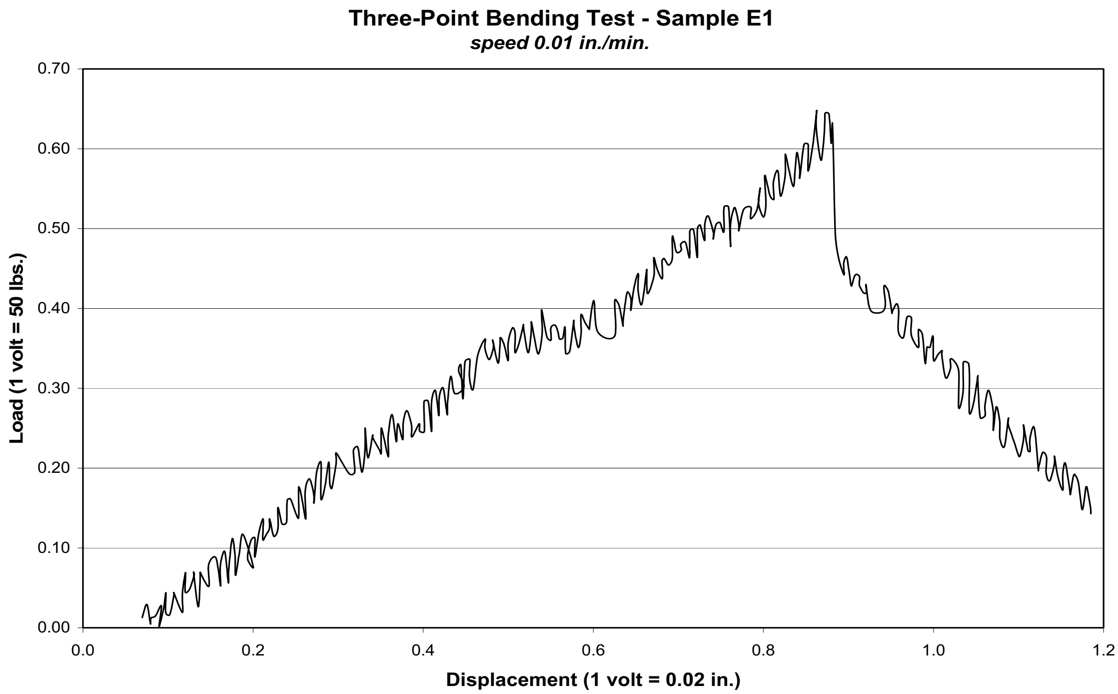
LOAD-DEFLECTION CURVES

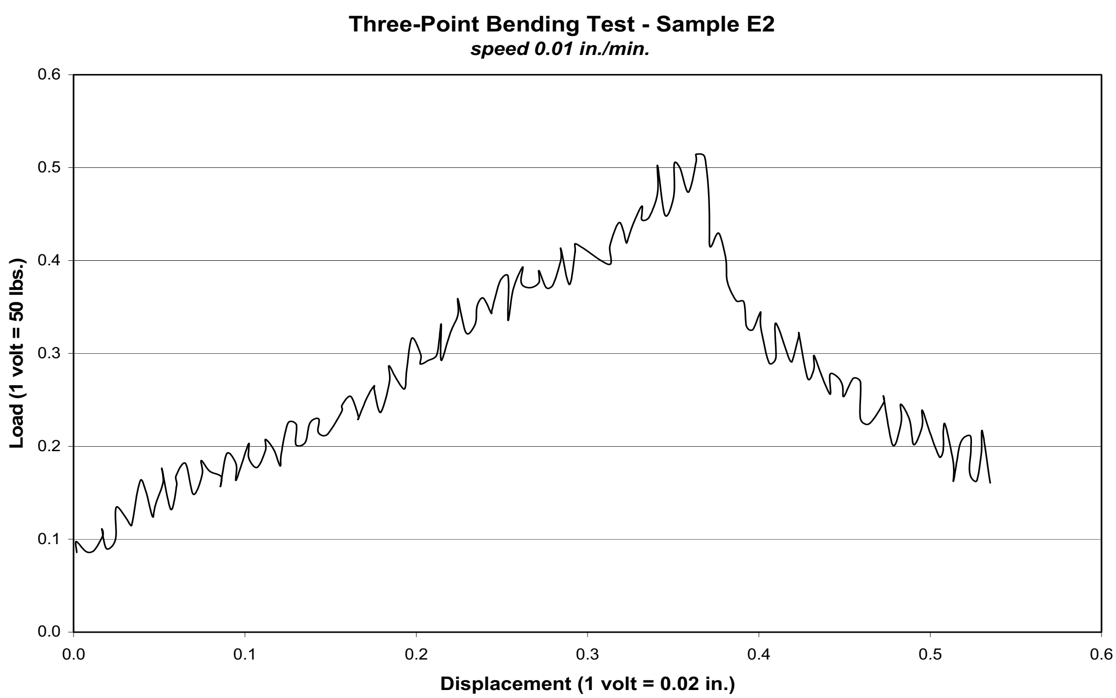




Appendix I: Flexural Test – ASTM C580-98

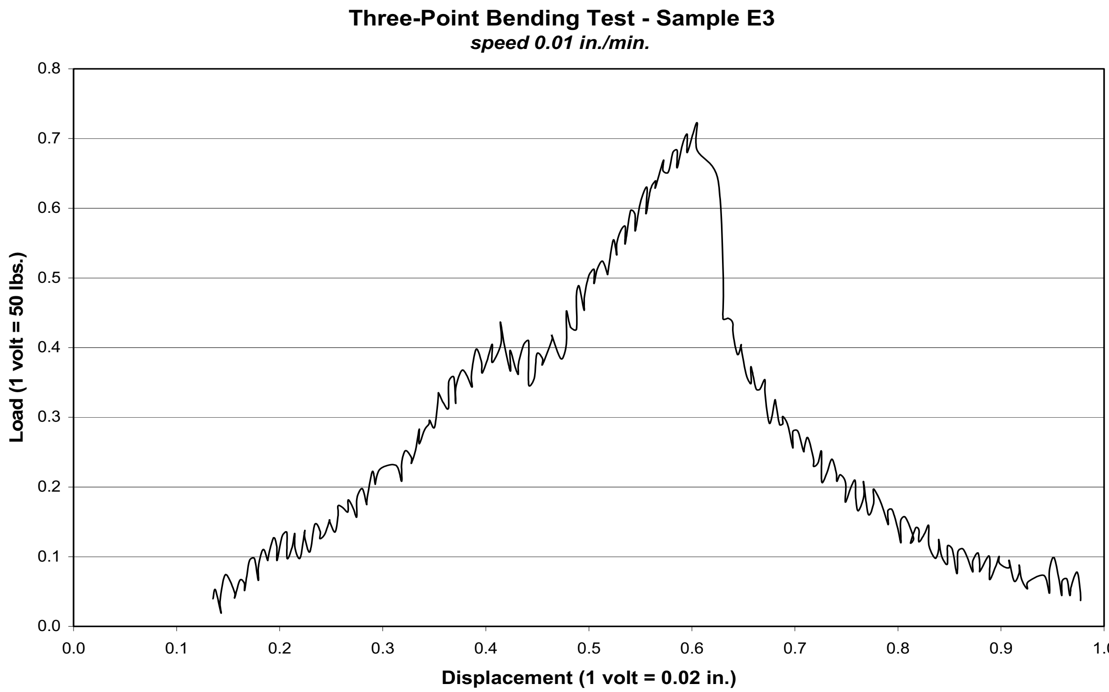
Load-Deflection Curves

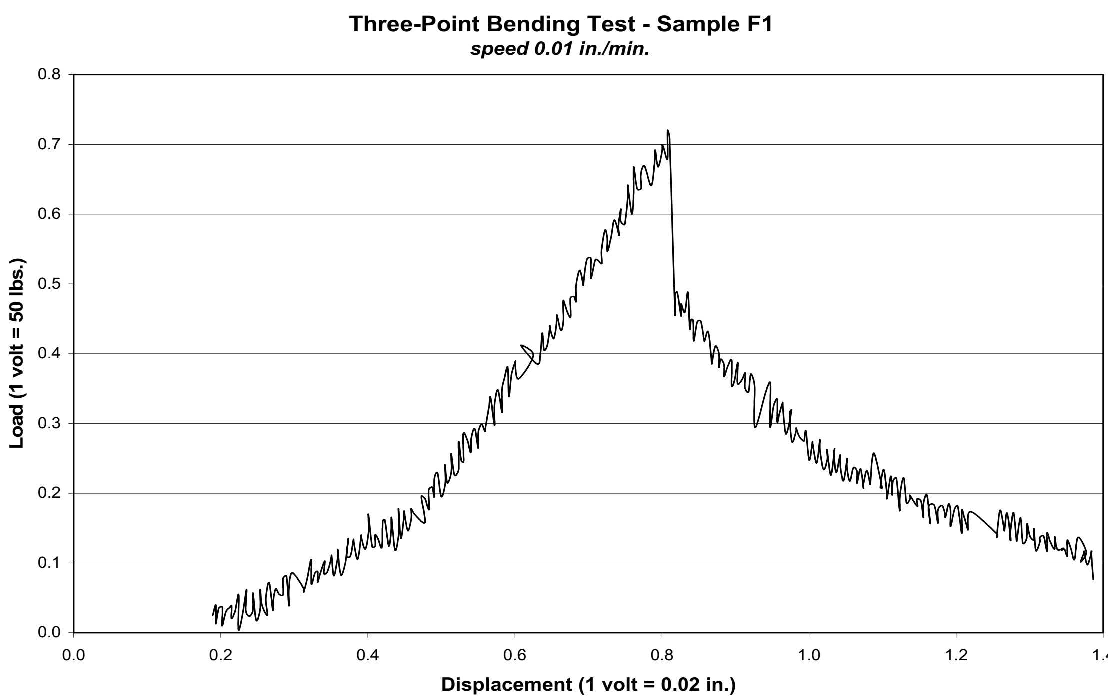




APPENDIX I: FLEXURAL TEST – ASTM C580-98

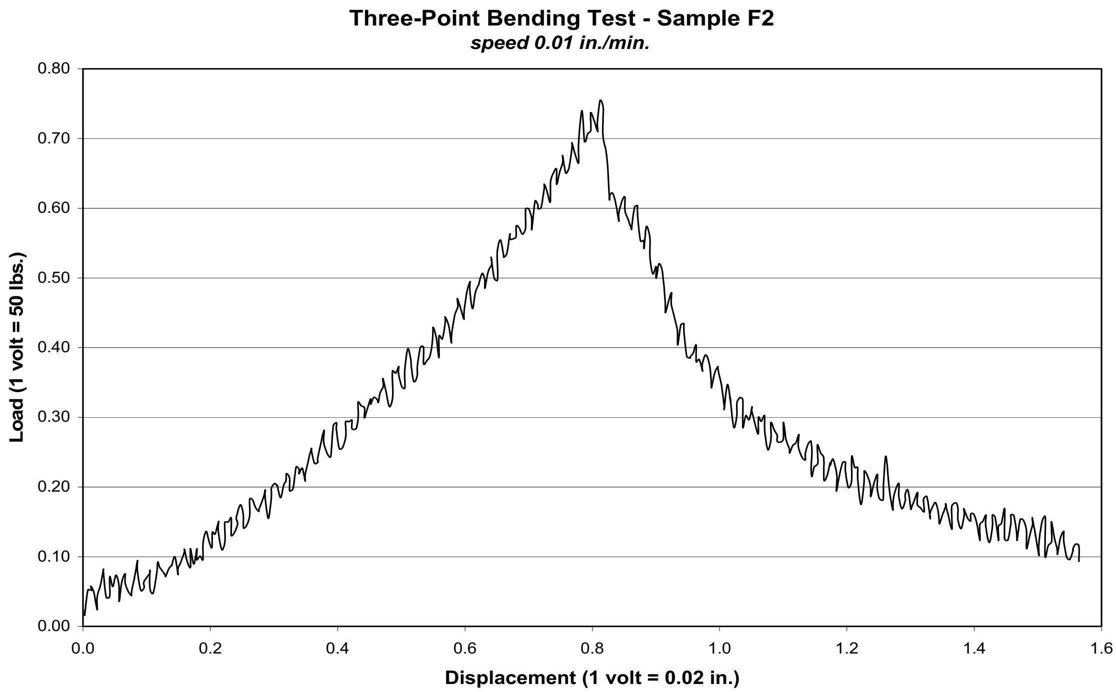
LOAD-DEFLECTION CURVES

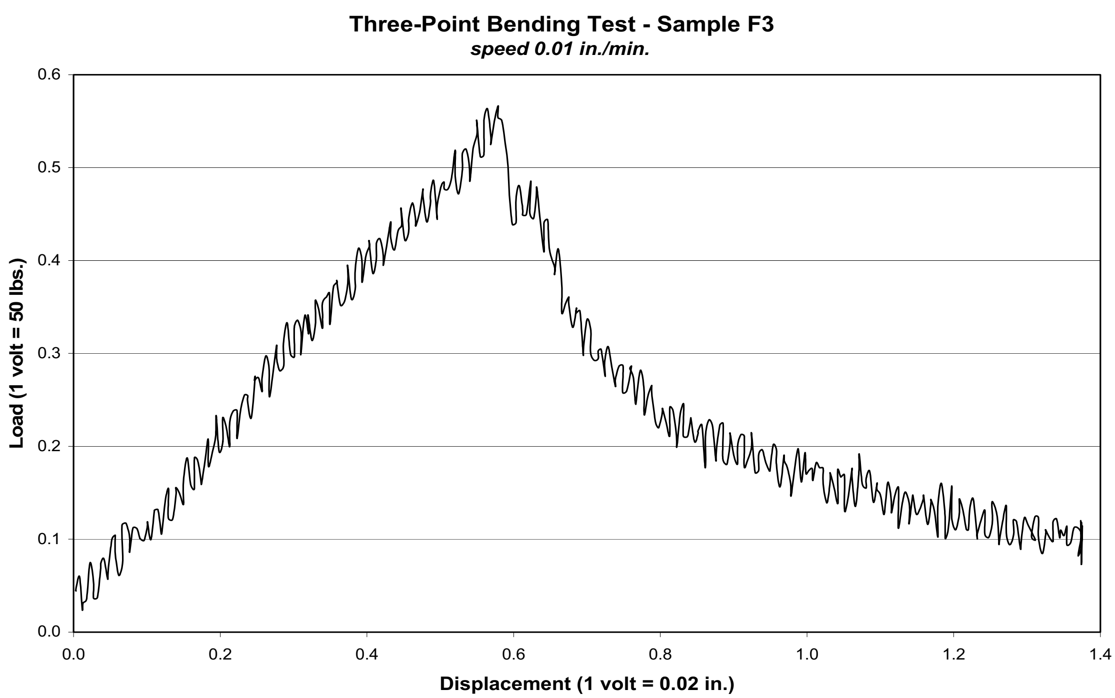




APPENDIX I: FLEXURAL TEST – ASTM C580-98

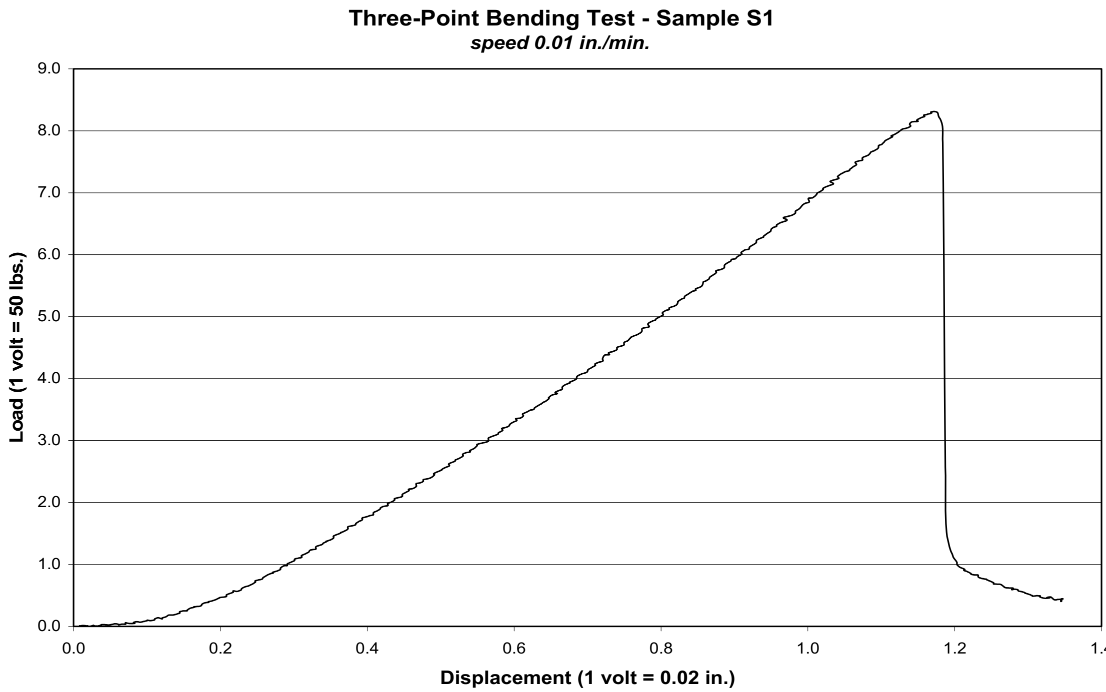
LOAD-DEFLECTION CURVES

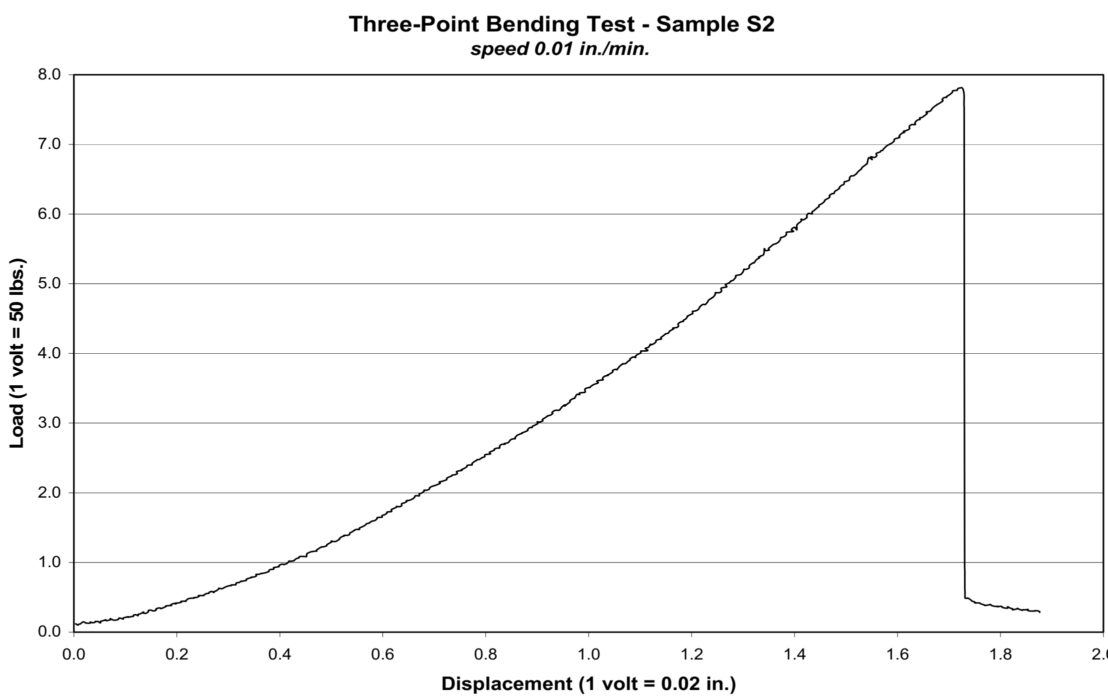




APPENDIX I: FLEXURAL TEST – ASTM C580-98

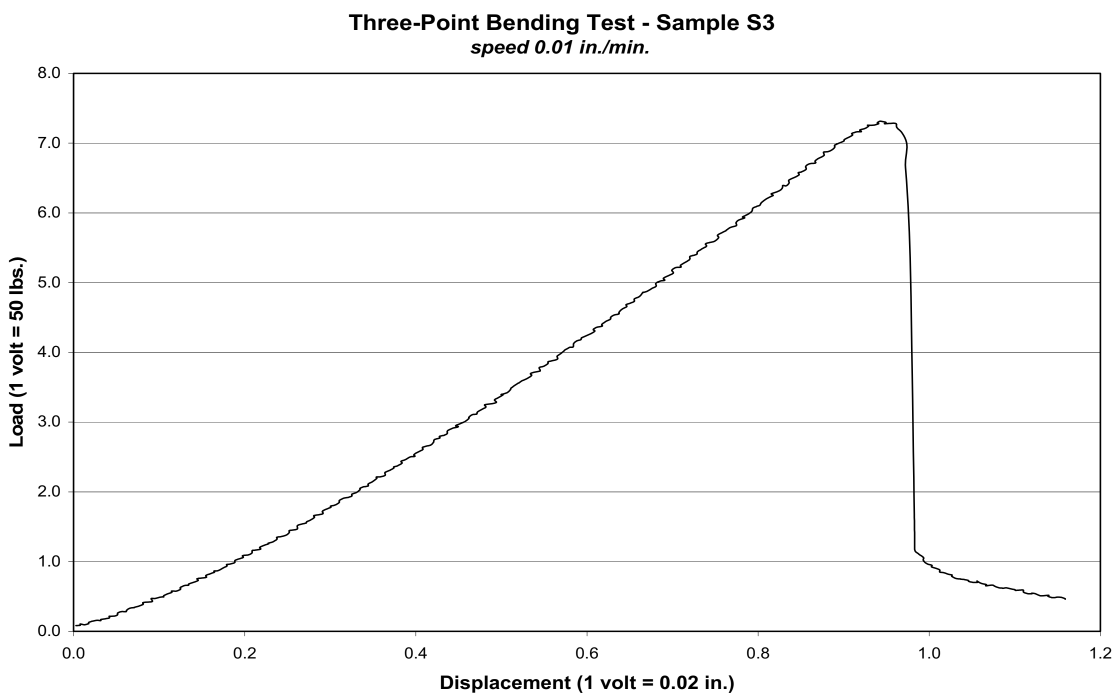
LOAD-DEFLECTION CURVES





APPENDIX I: FLEXURAL TEST – ASTM C580-98

LOAD-DEFLECTION CURVES



APPENDIX J: SALT CRYSTALLIZATION RESISTANCE – RILEM V.1B

WEIGHT MEASUREMENTS AND WEIGHT CHANGE CALCULATIONS

Sample	Initial weight (g)	Cycles 2		Cycles 4		Cycles 6	
		Weight (g)	Weight change (%)	Weight (g)	Weight change (%)	Weight (g)	Weight change (%)
A1	237.64	247.17	4.01	250.73	5.51	252.76	6.36
A2	239.91	249.17	3.86	251.31	4.75	255.37	6.44
A3	236.35	245.48	3.86	249.93	5.75	252.85	6.98
B1	238.69	246.25	3.17	249.73	4.63	254.36	6.57
B2	230.53	237.80	3.15	241.59	4.80	245.51	6.50
B3	235.84	243.04	3.05	247.25	4.84	250.99	6.42
C1	247.83	254.66	2.76	258.41	4.27	258.61	4.35
C2	248.88	255.67	2.73	259.61	4.31	259.22	4.15
C3	248.98	255.63	2.67	260.44	4.60	260.28	4.54
D1	227.74	234.59	3.01	235.21	3.28	233.73	2.63
D2	226.53	233.11	2.90	233.66	3.15	232.05	2.44
D3	232.03	238.73	2.89	240.16	3.50	234.03	0.86
E1	233.86	242.43	3.66	246.33	5.33	249.94	6.88
E2	226.12	234.47	3.69	233.38	3.21	240.54	6.38
E3	233.50	241.94	3.61	241.32	3.35	246.78	5.69
F1	232.75	238.99	2.68	240.40	3.29	246.48	5.90
F2	232.42	238.50	2.62	239.77	3.16	245.67	5.70
F3	228.60	234.48	2.57	235.99	3.23	240.71	5.30

Key to Samples	
Group A	cement/lime putty mortars
Group B	cement/lime putty mortars with acrylic
Group C	feebly hydraulic lime mortars
Group D	feebly hydraulic lime mortars with acrylic
Group E	moderately hydraulic lime mortars
Group F	moderately hydraulic lime mortars with acrylic

Appendix J: Salt Crystallization Resistance – RILEM V.1b

Weight Measurements and Weight Change Calculations

Sample	Initial weight (g)	Cycles					
		8		10		12	
		Weight (g)	Weight change (%)	Weight (g)	Weight change (%)	Weight (g)	Weight change (%)
A1	237.64	252.45	6.23	254.39	7.05	255.75	7.62
A2	239.91	253.58	5.70	256.38	6.87	257.71	7.42
A3	236.35	250.19	5.86	254.28	7.59	255.08	7.92
B1	238.69	251.55	5.39	253.29	6.12	255	6.83
B2	230.53	242.32	5.11	244.92	6.24	246.05	6.73
B3	235.84	247.7	5.03	251.47	6.63	252.3	6.98
C1	247.83	sample broke and was eliminated					
C2	248.88	252.42	1.42	227.57	-8.56	225.4	-9.43
C3	248.98	221.81	-10.91	208.11	-16.41	205.36	-17.52
D1	227.74	227.78	0.02	224.91	-1.24	223.08	-2.05
D2	226.53	227.11	0.26	224.25	-1.01	224.1	-1.07
D3	232.03	230.62	-0.61	229.26	-1.19	229.34	-1.16
E1	233.86	248.83	6.40	248.76	6.37	251.41	7.50
E2	226.12	239.78	6.04	240.18	6.22	241.67	6.88
E3	233.50	246.4	5.52	246.55	5.59	249.04	6.66
F1	232.75	245.69	5.56	246.3	5.82	249.53	7.21
F2	232.42	244.97	5.40	245.69	5.71	249.14	7.19
F3	228.60	239.96	4.97	240.89	5.38	244.21	6.83

Key to Samples	
Group A	cement/lime putty mortars
Group B	cement/lime putty mortars with acrylic
Group C	feebly hydraulic lime mortars
Group D	feebly hydraulic lime mortars with acrylic
Group E	moderately hydraulic lime mortars
Group F	moderately hydraulic lime mortars with acrylic

Appendix J: Salt Crystallization Resistance – RILEM V.1b

Weight Measurements and Weight Change Calculations

Sample	Initial weight (g)	Cycles				After tap water immersion & drying	
		14		15			
		Weight (g)	Weight change (%)	Weight (g)	Weight change (%)	Weight (g)	Weight change (%)
A1	237.64	256.08	7.76	260.16	9.48	243.98	2.67
A2	239.91	257.69	7.41	259.43	8.14	246.55	2.77
A3	236.35	255.16	7.96	255.84	8.25	243.23	2.91
B1	238.69	255.3	6.96	258.96	8.49	245.41	2.82
B2	230.53	246.04	6.73	248.35	7.73	236.38	2.54
B3	235.84	252.39	7.02	253.63	7.54	242.79	2.95
C1	247.83	sample broke and was eliminated					
C2	248.88	222.71	-10.52	229.33	-7.86	203.23	-18.34
C3	248.98	202.65	-18.61	204.8	-17.74	187.91	-24.53
D1	227.74	221.03	-2.95	220.96	-2.98	207.56	-8.86
D2	226.53	223.61	-1.29	224.46	-0.91	205.98	-9.07
D3	232.03	227.25	-2.06	228.17	-1.66	214.86	-7.40
E1	233.86	251.82	7.68	252.74	8.07	237.80	1.68
E2	226.12	242.5	7.24	243.58	7.72	229.80	1.63
E3	233.50	249.22	6.73	250.61	7.33	236.15	1.13
F1	232.75	249.82	7.33	250.88	7.79	237.62	2.09
F2	232.42	248.97	7.12	250.07	7.59	237.44	2.16
F3	228.60	244.16	6.81	245.41	7.35	233.29	2.05

Key to Samples	
Group A	cement/lime putty mortars
Group B	cement/lime putty mortars with acrylic
Group C	feebly hydraulic lime mortars
Group D	feebly hydraulic lime mortars with acrylic
Group E	moderately hydraulic lime mortars
Group F	moderately hydraulic lime mortars with acrylic

APPENDIX J: SALT CRYSTALLIZATION – RILEM V.1B

PHOTOGRAPHS

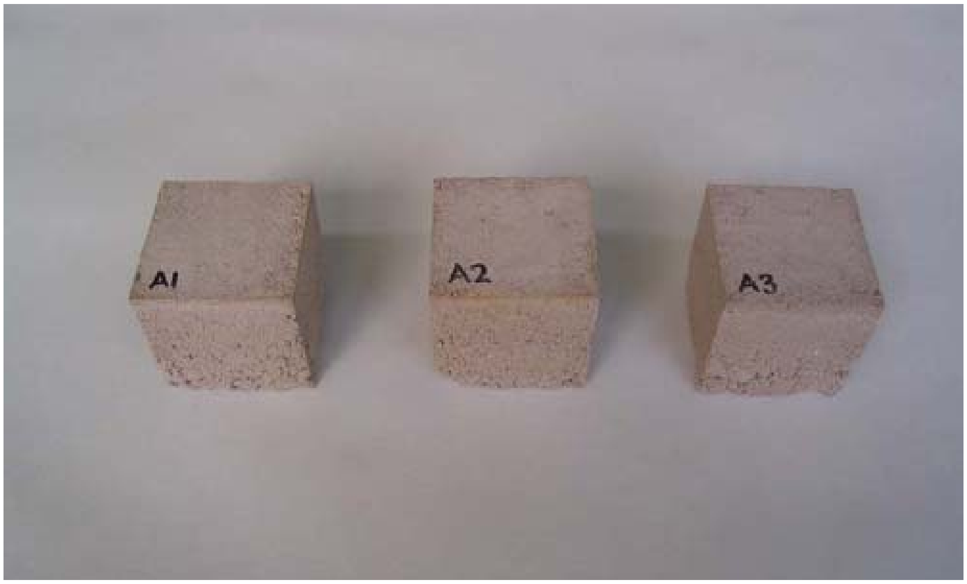


Figure J-1: The cement/lime putty samples before first cycle of 10% solution of sodium sulfate immersion, 7-day immersion in frequently renewed tap water, and drying in oven.

Figure J-2: The cement/lime putty samples after 15 cycles of 10% solution of sodium sulfate immersion, 7-day immersion in frequently renewed tap water, and drying in oven. Notice the minor disaggregation at the lower edges and corners.

PHOTOGRAPHS

Figure J-3: The cement/lime putty samples with Superior Additive 200 before first cycle of 10% solution of sodium sulfate immersion, 7-day immersion in frequently renewed tap water, and drying in oven.

Figure J-4: The cement/lime putty samples with Superior Additive 200 after 15 cycles of 10% solution of sodium sulfate immersion, 7-day immersion in frequently renewed tap water, and drying in oven. Notice minor disaggregation at the lower edges and corners indicating little to no effect of the acrylic emulsion.

APPENDIX J: SALT CRYSTALLIZATION – RILEM V.1B

PHOTOGRAPHS

Figure J-5: The feebly hydraulic lime samples before first cycle of 10% solution of sodium sulfate immersion, 7-day immersion in frequently renewed tap water, and drying in oven.

Figure J-6: The feebly hydraulic lime samples after 15 cycles of 10% solution of sodium sulfate immersion, 7-day immersion in frequently renewed tap water, and drying in oven. This sample set exhibits cracking and severe erosion of all surfaces. Note that sample C1 broke while immersed in salt solution during the 8th cycle.

APPENDIX J: SALT CRYSTALLIZATION – RILEM V.1B

PHOTOGRAPHS

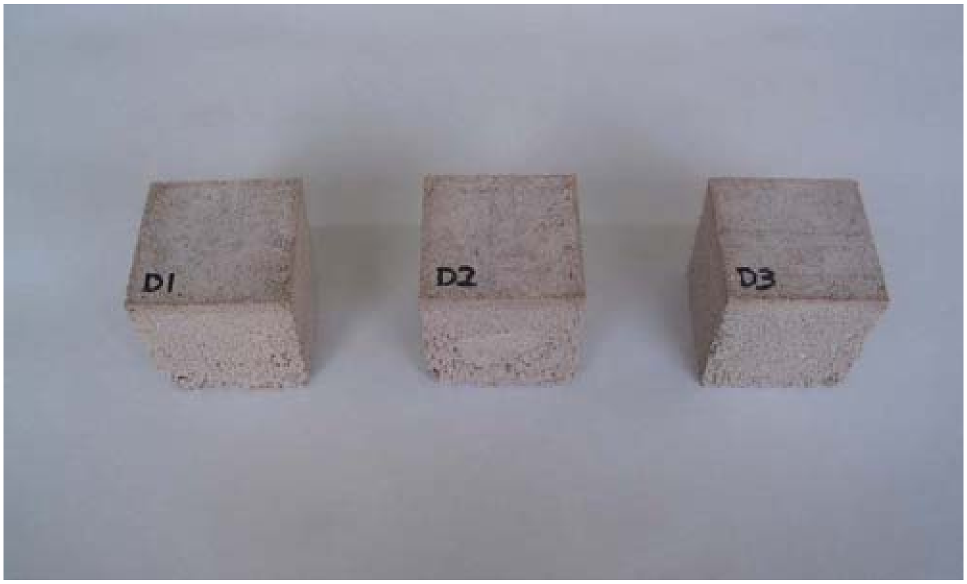


Figure J-7: The feebly hydraulic lime samples with Superior Additive 200 before first cycle of 10% solution of sodium sulfate immersion, 7-day immersion in frequently renewed tap water, and drying in oven.

Figure J-8: The feebly hydraulic lime samples with Superior Additive 200 after 15 cycles of 10% solution of sodium sulfate immersion, 7-day immersion in frequently renewed tap water, and drying in oven. This sample set exhibits erosion of all surfaces but to a lesser degree than Group C indicating increased salt resistance with the acrylic emulsion.

APPENDIX J: SALT CRYSTALLIZATION – RILEM V.1B

PHOTOGRAPHS

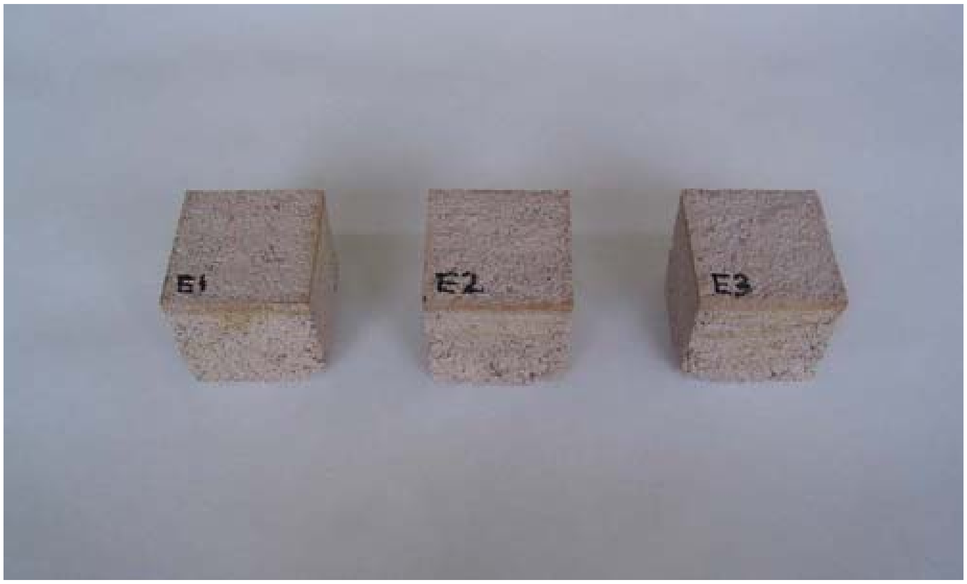


Figure J-9: The moderately hydraulic lime samples before first cycle of 10% solution of sodium sulfate immersion, 7-day immersion in frequently renewed tap water, and drying in oven.

Figure J-10: The moderately hydraulic lime samples after 15 cycles of 10% solution of sodium sulfate immersion, 7-day immersion in frequently renewed tap water, and drying in oven. No change in shape or edges of E1 and E2, but E3 exhibits minor disaggregation at the corners and edges.

Appendix J: Salt Crystallization – RILEM V.1b

Photographs

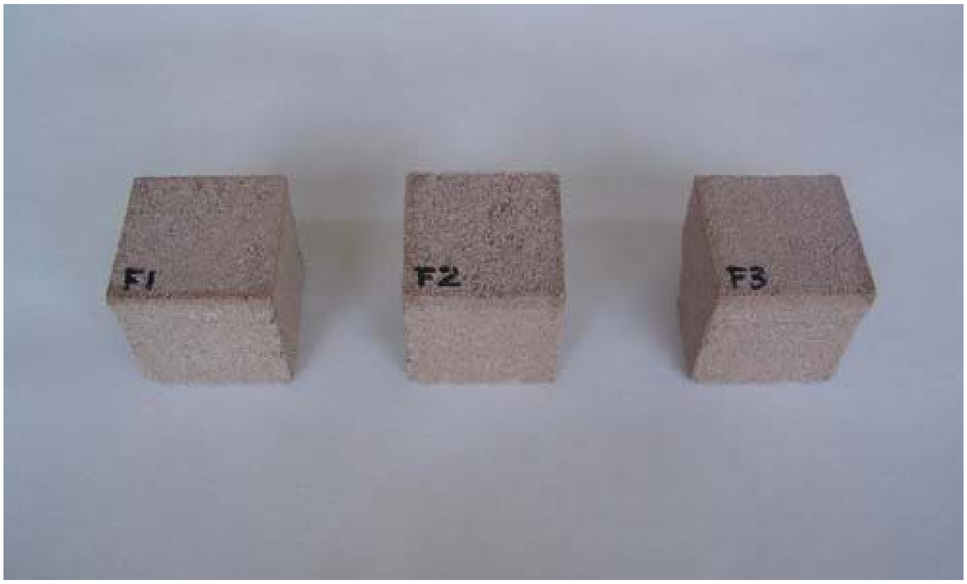


Figure J-11: The moderately hydraulic lime samples with Superior Additive 200 before first cycle of 10% solution of sodium sulfate immersion, 7-day immersion in frequently renewed tap water, and drying in oven.

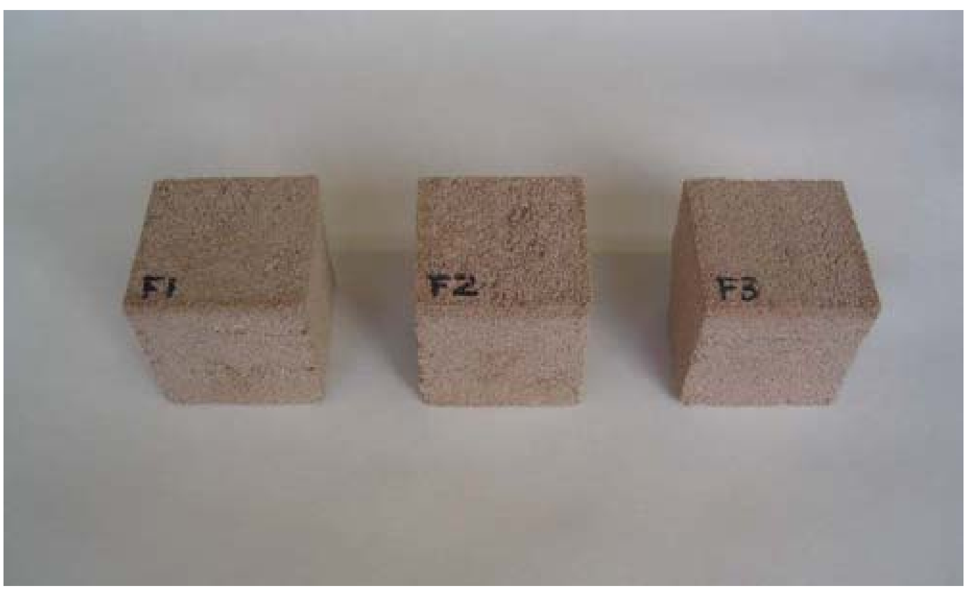


Figure J-12: The moderately hydraulic lime samples with Superior Additive 200 after 15 cycles of 10% solution of sodium sulfate immersion, 7-day immersion in frequently renewed tap water, and drying in oven. This sample set exhibits little to no erosion indicating a minor improvement in salt resistance with the acrylic emulsion.

APPENDIX K: FROST RESISTANCE – RILEM V.3

BULK VOLUME CALCULATIONS

Sample	Initial weight in air (g)	Initial weight in water (g)	Initial bulk volume	4 Cycles			
				Weight in air (g)	Weight in water (g)	Bulk volume (g)	% Bulk volume retained
A1	261.38	135.96	125.42	264.36	140.48	123.88	98.77
A2	268.32	139.37	128.95	271.20	142.51	128.69	99.80
A3	262.16	136.30	125.86	265.28	136.99	128.29	101.93
B1	274.26	146.19	128.07	276.66	148.27	128.39	100.25
B2	269.36	142.63	126.73	271.64	145.39	126.25	99.62
B3	273.16	144.09	129.07	276.18	147.01	129.17	100.08
C1	277.32	147.86	129.46	279.26	149.72	129.54	100.06
C2	287.55	155.01	132.54	289.18	156.32	132.86	100.24
C3	277.31	148.55	128.76	279.34	149.82	129.52	100.59
D1	252.22	129.01	123.21	251.22	129.82	121.40	98.53
D2	256.70	130.63	126.07	254.95	131.51	123.44	97.91
D3	254.90	129.98	124.92	265.05	131.97	133.08	106.53
E1	247.56	123.72	123.84	249.35	127.01	122.34	98.79
E2	243.45	121.62	121.83	239.58	121.81	117.77	96.67
E3	250.05	126.06	123.99	248.40	126.99	121.41	97.92
F1	251.58	123.07	128.51	256.65	129.17	127.48	99.20
F2	258.00	129.05	128.95	261.96	133.35	128.61	99.74
F3	260.83	129.92	130.91	266.23	135.23	131.00	100.07

Key to Samples	
Group A	cement/lime putty mortars
Group B	cement/lime putty mortars with acrylic
Group C	feebly hydraulic lime mortars
Group D	feebly hydraulic lime mortars with acrylic
Group E	moderately hydraulic lime mortars
Group F	moderately hydraulic lime mortars with acrylic

APPENDIX K: FROST RESISTANCE – RILEM V.3

BULK VOLUME CALCULATIONS

Sample	Initial weight in air (g)	Initial weight in water (g)	Initial bulk volume	8 Cycles			
				Weight in air (g)	Weight in water (g)	Bulk volume (g)	% Bulk volume retained
A1	261.38	135.96	125.42	265.49	139.70	125.79	100.30
A2	268.32	139.37	128.95	271.91	143.40	128.51	99.66
A3	262.16	136.30	125.86	265.93	140.24	125.69	99.86
B1	274.26	146.19	128.07	277.40	149.15	128.25	100.14
B2	269.36	142.63	126.73	272.59	145.53	127.06	100.26
B3	273.16	144.09	129.07	277.00	147.85	129.15	100.06
C1	277.32	147.86	129.46	278.96	149.50	129.46	100.00
C2	287.55	155.01	132.54	289.90	156.10	133.80	100.95
C3	277.31	148.55	128.76	279.78	149.05	130.73	101.53
D1	252.22	129.01	123.21	158.93	82.00	76.93	62.44
D2	256.70	130.63	126.07	159.67	82.95	76.72	60.86
D3	254.90	129.98	124.92	172.68	88.17	84.51	67.65
E1	247.56	123.72	123.84	238.73	120.40	118.33	95.55
E2	243.45	121.62	121.83	209.73	106.71	103.02	84.56
E3	250.05	126.06	123.99	240.82	123.25	117.57	94.82
F1	251.58	123.07	128.51	257.43	129.32	128.11	99.69
F2	258.00	129.05	128.95	262.82	134.24	128.58	99.71
F3	260.83	129.92	130.91	267.79	135.82	131.97	100.81

Key to Samples	
Group A	cement/lime putty mortars
Group B	cement/lime putty mortars with acrylic
Group C	feebly hydraulic lime mortars
Group D	feebly hydraulic lime mortars with acrylic
Group E	moderately hydraulic lime mortars
Group F	moderately hydraulic lime mortars with acrylic

Appendix K: Frost Resistance – RILEM V.3

Bulk Volume Calculations

Sample	Initial weight in air (g)	Initial weight in water (g)	Initial bulk volume	12 Cycles			
				Weight in air (g)	Weight in water (g)	Bulk volume (g)	% Bulk volume retained
A1	261.38	135.96	125.42	265.92	140.40	125.52	100.08
A2	268.32	139.37	128.95	271.64	143.74	127.90	99.19
A3	262.16	136.30	125.86	266.80	140.48	126.32	100.37
B1	274.26	146.19	128.07	277.90	149.40	128.50	100.34
B2	269.36	142.63	126.73	273.10	146.25	126.85	100.09
B3	273.16	144.09	129.07	277.63	148.31	129.32	100.19
C1	277.32	147.86	129.46	261.64	139.54	122.10	94.31
C2	287.55	155.01	132.54	273.94	147.37	126.57	95.50
C3	277.31	148.55	128.76	255.75	135.30	120.45	93.55
D1	252.22	129.01	123.21	113.36	57.99	55.37	44.94
D2	256.70	130.63	126.07	95.19	48.28	46.91	37.21
D3	254.90	129.98	124.92	107.88	54.45	53.43	42.77
E1	247.56	123.72	123.84	138.27	68.98	69.29	55.95
E2	243.45	121.62	121.83	sample broke and was eliminated			
E3	250.05	126.06	123.99	166.94	83.51	83.43	67.29
F1	251.58	123.07	128.51	258.22	129.69	128.53	100.02
F2	258.00	129.05	128.95	264.94	134.55	130.39	101.12
F3	260.83	129.92	130.91	267.67	136.05	131.62	100.54

Key to Samples	
Group A	cement/lime putty mortars
Group B	cement/lime putty mortars with acrylic
Group C	feebly hydraulic lime mortars
Group D	feebly hydraulic lime mortars with acrylic
Group E	moderately hydraulic lime mortars
Group F	moderately hydraulic lime mortars with acrylic

APPENDIX K: FROST RESISTANCE – RILEM V.3

BULK VOLUME CALCULATIONS

Sample	Initial weight in air (g)	Initial weight in water (g)	Initial bulk volume	15 Cycles			
				Weight in air (g)	Weight in water (g)	Bulk volume (g)	% Bulk volume retained
A1	261.38	135.96	125.42	265.84	138.40	127.44	101.61
A2	268.32	139.37	128.95	270.95	141.23	129.72	100.60
A3	262.16	136.30	125.86	266.45	140.66	125.79	99.94
B1	274.26	146.19	128.07	277.94	149.40	128.54	100.37
B2	269.36	142.63	126.73	273.19	146.38	126.81	100.06
B3	273.16	144.09	129.07	277.78	148.39	129.39	100.25
C1	277.32	147.86	129.46	240.25	127.90	112.35	86.78
C2	287.55	155.01	132.54	256.69	137.30	119.39	90.08
C3	277.31	148.55	128.76	238.00	126.65	111.35	86.48
D1	252.22	129.01	123.21	92.07	46.50	45.57	36.99
D2	256.70	130.63	126.07	76.05	38.69	37.36	29.63
D3	254.90	129.98	124.92	79.51	38.84	40.67	32.56
E1	247.56	123.72	123.84	118.23	58.21	60.02	48.47
E2	243.45	121.62	121.83	sample broke and was eliminated			
E3	250.05	126.06	123.99	156.47	78.09	78.38	63.21
F1	251.58	123.07	128.51	255.20	127.65	127.55	99.25
F2	258.00	129.05	128.95	265.74	133.68	132.06	102.41
F3	260.83	129.92	130.91	265.33	132.69	132.64	101.32

Key to Samples	
Group A	cement/lime putty mortars
Group B	cement/lime putty mortars with acrylic
Group C	feebly hydraulic lime mortars
Group D	feebly hydraulic lime mortars with acrylic
Group E	moderately hydraulic lime mortars
Group F	moderately hydraulic lime mortars with acrylic

APPENDIX K: FROST RESISTANCE – RILEM V.3

PHOTOGRAPHS

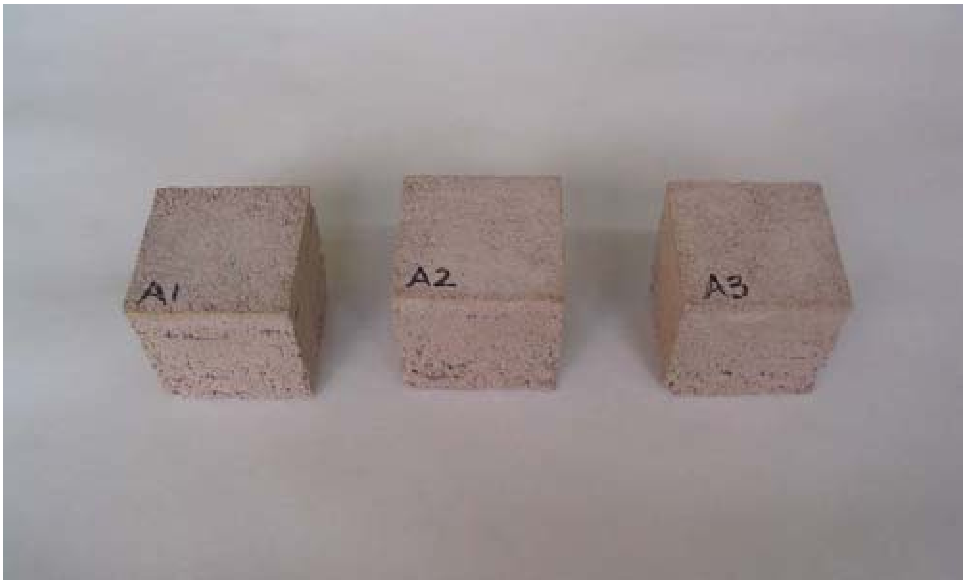


Figure K-1: Cement/lime putty samples before 6-hour immersion and first freeze/thaw cycle.

Figure K-2: Cement/lime putty samples after 6-hour immersion and 15 freeze/thaw cycles. No change in shape or edges of A1, but A2 and A3 exhibit minor disaggregation at the lower corners.

APPENDIX K: FROST RESISTANCE – RILEM V.3

PHOTOGRAPHS

Figure K-3: Cement/lime putty samples with Superior Additive 200 before 6-hour immersion and first freeze/thaw cycle.

Figure K-4: Cement/lime putty samples with Superior Additive 200 after 6-hour immersion and 15 freeze/thaw cycles. No change in shape or edges and corners occurred indicating that the acrylic emulsion had only a minor effect on frost resistance.

APPENDIX K: FROST RESISTANCE – RILEM V.3

PHOTOGRAPHS

Figure K-5: Feebly hydraulic lime samples before 6-hour immersion and first freeze/thaw cycle.

Figure K-6: Feebly hydraulic lime samples after 6-hour immersion and 15 freeze/thaw cycles. This sample set exhibits significant erosion of all surfaces, edges, and corners.

APPENDIX K: FROST RESISTANCE – RILEM V.3

PHOTOGRAPHS

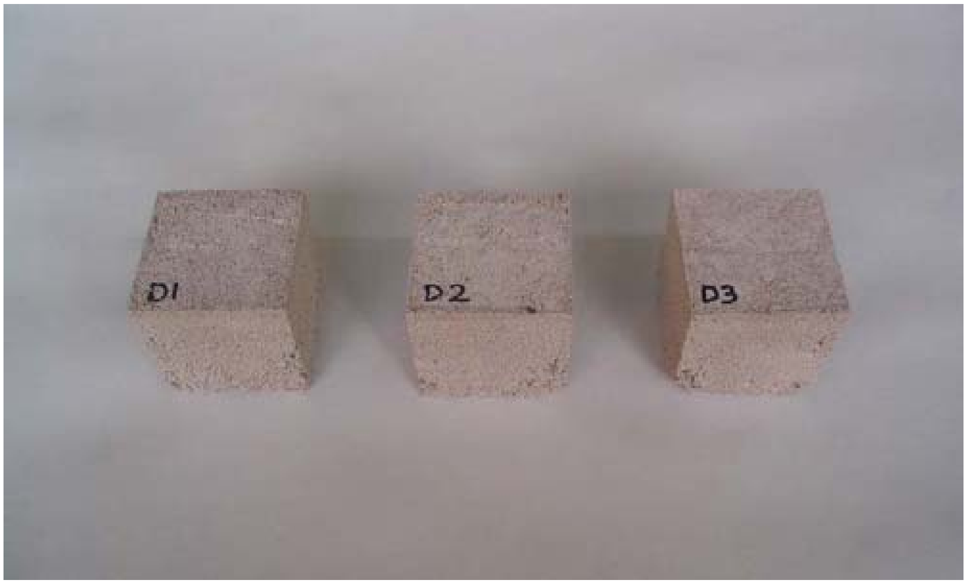


Figure K-7: Feebly hydraulic lime samples with Superior Additive 200 before 6-hour immersion and first freeze/thaw cycle.

Figure K-8: Feebly hydraulic lime samples with Superior Additive 200 after 6-hour immersion and 15 freeze/thaw cycles. This samples set exhibits even greater erosion than Group C indicating that the acrylic emulsion significantly decreased frost resistance.

APPENDIX K: FROST RESISTANCE – RILEM V.3

PHOTOGRAPHS

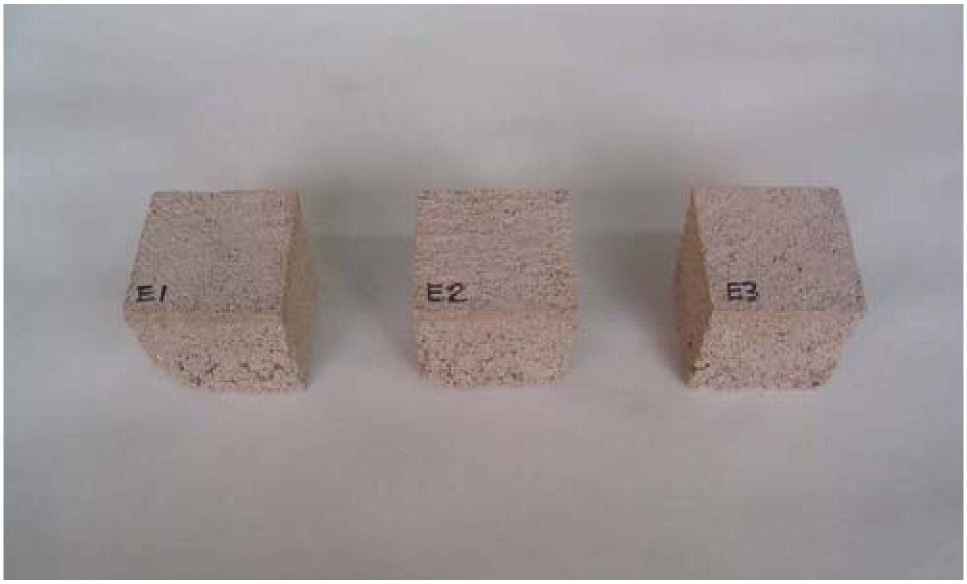


Figure K-9: Moderately hydraulic lime samples before 6-hour immersion and first freeze/thaw cycle.

Figure K-10: Moderately hydraulic lime samples after 6-hour immersion and15 freeze/thaw cycles. This sample set exhibits severe deterioration with complete loss of original shape. Note that sample E2 broke while being weighed after the 8th cycle.

APPENDIX K: FROST RESISTANCE – RILEM V.3

PHOTOGRAPHS

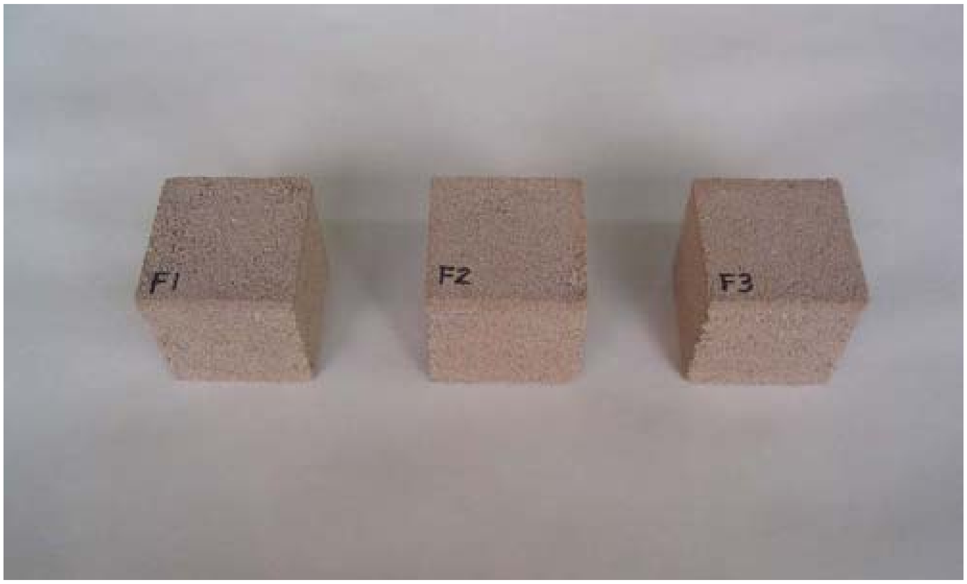


Figure K-11: Moderately hydraulic lime samples with Superior Additive 200 before 6-hour immersion and first freeze/thaw cycle.

Figure K-12: Moderately hydraulic lime samples with Superior Additive 200 after 6-hour immersion and 15 freeze/thaw cycles. Although this sample set retained most of its bulk density, all three samples broke along horizontal lines while being weighed at the end of the test. Though the pattern of deterioration is different from Group E, the acrylic emulsion did not improve overall frost resistance.

APPENDIX L: MATERIAL SUPPLIERS

CAVA Building Supply
2007 Washington Avenue
Philadelphia, PA 19146
Phone: (215) 732-0907
Fax: (215) 545-7045
Internet: www.cavabuilding.com
Email: service@cavabuilding.com
Materials: Niagara Mature Lime Putty – (2) 3 gallon buckets

George F. Kempf Supply Company
5800 Lindbergh Boulevard
Philadelphia, PA 19143
Phone: (215) 724-8000
Materials: Lehigh White Portland Cement Type I – (1) 94 pound bag

George Schofield Company
831 East Main Street
Bridgewater, NJ 08807
Phone: (732) 356-0858 / Toll Free: (800) 827-6257
Fax: (732) 356-1137
Internet: www.geoschofield.com
Email: Rocks@geoschofield.com
Materials: #236 Reddish Mason Sand – (6) 50 pound bags

El Rey Stucco Company
50 Rio Grande Boulevard
Denver, CO 80223
Phone: (303) 534-3536 / Toll Free: (888) 463-5739
Fax: (303) 534-3141
Internet: www.elrey.com
Email: info@elrey.com
Materials: Superior Additive 200 – (1) 5 gallon bucket

Pennsylvania Lime Works
P.O. Box 151
Milford Square, PA 18935
Phone: (215) 536-6706
Fax: (215) 536-2281
Internet: www.palimeworks.com
Email: helpme@repointing.com
Materials: St. Astier NHL 2 & 3.5 – (2) 55 pound bags each

INDEX